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NOTES ON THE STRATIGRAPHY OF THE MOAB REGION, UTAH[1]

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ABSTRACT

Results of work near Moab, Utah, by U. S. Geological Survey field parties in 1926 in part accord with and in part differ from current interpretations. In the Salt Valley anticline lower Mississippian rocks occur as limestone boulders in a conglomerate of unknown age. The oldest rocks in place at the surface are Pennsylvanian (Hermosa formation), sharply separated from the Permian by contained marine faunas. The Permian formations (Rico and Cutler) are not sharply separated. The former contains marine limestones; the latter, tongues of white sandstone that increase southwestward and at top the sandstone member (De Chelly?) locally known as the White Rim. The Lower Triassic Moenkopi formation, including in Green River Valley a marine limestone member, rests with unconformity upon Cutler and is in turn overlain unconformably by Upper(?) Triassic Shinarump conglomerate. Shinarump grades upward into the Chinle formation and is not recognizable as a separate unit at many localities, especially toward the east. A group of Jurassic(?) formations, including Wingate and Navajo sandstones separated by the Todilto(?) formation, rests unconformably upon the Chinle. The formations of the group are conformable and have arbitrary common boundaries. The succeeding Carmel and Entrada formations (Upper Jurassic) are similar to this group. The Carmel formation may overlie the Navajo sandstone with unconformity. Summerville formation (Upper Jurassic) intertongues with the underlying Entrada sandstone so that Entrada lithology extends higher toward the east. Summerville is separated by an unconformity from the overlying Salt Wash sandstone member of the Morrison formation (Cretaceous?). Dakota(?) sandstone (Upper Cretaceous) rests unconformably upon the Morrison formation and is succeeded by the Mancos shale.

The stratigraphy would seem to indicate the following events in the history of the region: Possibly folding and erosion between lower Mississippian and Pennsylvanian; folding and erosion at the close of the Permian; erosion and possibly folding between Lower and Upper Triassic, and between Upper Triassic and Jurassic(?) (Wingate); possibly erosion preceding Upper Jurassic (Carmel); erosion between Upper Jurassic and Cretaceous(?) (Morrison), and between Cretaceous(?) and Upper Cretaceous.

[1] Presented by title before the Association, Tulsa meeting, March 26, 1927. Manuscript received by the editor May 13, 1927. Published by permission of the director of the U. S. Geological Survey.

INTRODUCTION

A preliminary statement of some of the results of field work in 1926 in the Moab region, eastern Utah, it is believed, will be useful as an extension and partial revision of data already recorded by other students of the region and as an attempt to outline more clearly some of the stratigraphic problems still awaiting solution.

During the field work Mr. Baker mapped in detail a triangular area southeast of Colorado River, extending from the mouth of Lockhart Canyon and the north rim of Indian Creek Valley northward to Castle Creek and eastward from the river to the east line of R. 23 E. Mr. Mc Knight mapped the area between Green and Colorado rivers extending from their junction northward to Moab Valley and to the south side of T. 23 S., a distance of about 40 miles. The detailed mapping covered a total area of approximately 1,200 square miles. Mr. Dobbin and Mr. Reeside visited many localities in the region and made a reconnaissance of type localities of formations in the San Juan Mountain region and in San Juan River Valley. The writers in company examined typical sections of the rocks in San Rafael Swell and in Green River Desert.

G. H. Girty identified the fossils collected from the Hermosa, Rico, and Moenkopi formations and made a report on them which has been of great service to us, especially in making comparisons with other regions.

Recent papers by Prommel,[1] Harrison,[2] and Prommel and Crum[3] discuss the stratigraphy, structure, and geologic history of the region. A *Department of the Interior Memorandum for the Press*, issued March 30, 1926, also applies to the region and as regards stratigraphic terminology is largely followed in the present paper.

STRATIGRAPHIC DIVISIONS

The names adopted in the present paper for the stratigraphic units recognized in the Moab region, together with summary descriptions, are shown in Table I.

PRE-PENNSYLVANIAN ROCKS

A conglomerate exposed in Salt Valley contains boulders of limestone and chert as much as 15 inches in diameter imbedded in a well-

[1] H. W. C. Prommel, "Portions of Grand and San Juan Counties, Utah," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 384–99.

[2] T. S. Harrison, "Colorado-Utah Salt Domes," *ibid.*, Vol. 11 (1927), pp. 111–33.

[3] H. W. C. Prommel and H. E. Crum, "Salt Domes of Permian and Pennsylvanian Age in Southeastern Utah and Their Influence on Oil Accumulation," *ibid.*, pp. 373–93.

indurated yellow sandstone matrix. All the fossils found in them are either Mississippian or longer-ranging species that could be Mississippian. The outcrop is isolated and its relations are difficult to determine because of complicated structure and poor exposures. It may be as old as upper Mississippian or it may be much younger. The absence of abundant later

TABLE I

FORMATIONS OF THE MOAB REGION, UTAH

System	Series	Group and Formation	Thickness (Feet)	Description
Cretaceous	Upper Cretaceous	Mancos shale		Steel-gray shale with subordinate sandstone members. Marine fossils throughout
		Dakota (?) sandstone	0–180	Variable gray to brown sandstone, conglomerate of siliceous pebbles
	Erosional unconformity			
Cretaceous(?)		Morrison formation	540–850	Upper part: variegated chocolate, red, gray, green, and purple mudstone and shale, with minor gray sandstone and conglomerate, in part siliceous. Lower part (Salt Wash sandstone member): gray-white sandstone and reddish shaly sandstones
	Erosional unconformity			
Jurassic	Upper Jurassic	San Rafael group: Summerville formation	50–100	Chocolate-colored to red shaly sandstone containing many crusts and large nodular aggregations of silica. Intertongues with underlying formation
		San Rafael group: Entrada sandstone	300–400	Light-gray to orange-brown, cross-bedded, medium-grained massive sandstone. Moab tongue at top, lighter in color, thins out westward into Summerville formation
		San Rafael group: Carmel formation	35–125	Red, earthy, thin-bedded sandstone, and minor sandy shale. Bedding usually contorted. Cut out locally by sandstone like overlying Entrada
	Erosional unconformity (?)			
Jurassic(?)		Glen Canyon group: Navajo sandstone	300–450	Gray-white to light-brown, massive, much cross-bedded, medium-grained sandstone; occasional thin brown and gray limestone lenses
		Glen Canyon group: Todilto(?) formation	250	Irregularly bedded sandstone, red near base, buff and lavender near top; subordinate red sandy shale; and rarely thin impure limestone. Fresh-water fossils
		Glen Canyon group: Wingate sandstone	300–350	Gray or tan to brownish-red, massive, much cross-bedded, medium-grained sandstone with characteristic vertical joints

TABLE I—*Continued*

System	Series	Group and Formation	Thickness (Feet)	Description
Unconformity—erosion and possibly folding				
Triassic	Upper Triassic	Chinle formation	200–750	Red and greenish sandy mudstone or sandstone, conglomerate of quartz and limestone pebbles, and conglomerates of pellets of gray limestone and mud, all irregularly bedded. Fresh-water shells, reptilian bones and teeth, and silicified wood
	Upper Triassic(?)	Shinarump conglomerate	0–200	Light-brown conglomeratic sandstone, the pebbles in large part siliceous. Not definitely recognized at many localities toward the east
	Unconformity—erosion and possibly folding			
	Lower Triassic	Moenkopi formation	0–600	Chocolate-colored to red-brown, ripple-marked, evenly bedded shaly sandstones. In Green River Valley contains near middle a thin marine limestone member (Sinbad limestone member) near base of a thick zone of light greenish-gray sandy shale
Unconformity—erosion and folding				
Permian		Cutler formation	0–600	Maroon and purplish-red arkose, sandstone, and conglomerate; a few beds of sandy mudstone. Tongues of gray-white sandstone appear in west and thicken southwestward. Bedding in the large, regular; in detail, irregular. De Chelly (?) sandstone member forms top in region west of Colorado River
		Rico formation	0–600	Red and purple sandstone and shale, and more or less gray to brown or greenish sandy limestone with abundant marine fossils. At some localities where limestone is unimportant the unit is not sharply separated from the overlying Cutler formation. In the south and west a bed locally called "Shafer limestone" is the top of the formation
Pennsylvanian		Hermosa formation	800+	Gray to brownish limestone and light greenish-gray massive sandstone. Locally blue-green limestone and red arkosic sandstone occur. Marine fossils abundant. Base not exposed

types of rock as boulders and of post-Mississippian fossils suggests an early age, but more evidence is needed before any definite assignment can be made. The nearest present-day outcrop from which the lower Mississippian boulders could have come is about 125 miles distant. No comparable conglomerate is known in any of the formations cropping out in the region, so far as the writers are informed.

The fossils found in the boulders, as determined by G. H. Girty, are:

Boulder 1. *Schizophoria?* sp., *Schuchertella* aff. *S. chemungensis, Spiriferina solidirostris, Composita humilis?, Cliothyridina?* sp.

Boulder 2. *Tripolophyllum* sp., *Fenestella*, several species, *Schizophoria sedaliensis?, Camarotoechia* aff. *C. metallica, Camarotoechia* sp., *Camarophoria bisinuata?, Spirifer* sp., *Spiriferina* sp., *Pseudosyrinx* aff. *keokuk.*

Boulder 3. *Triplophyllum* sp., *Schuchertella?* sp.

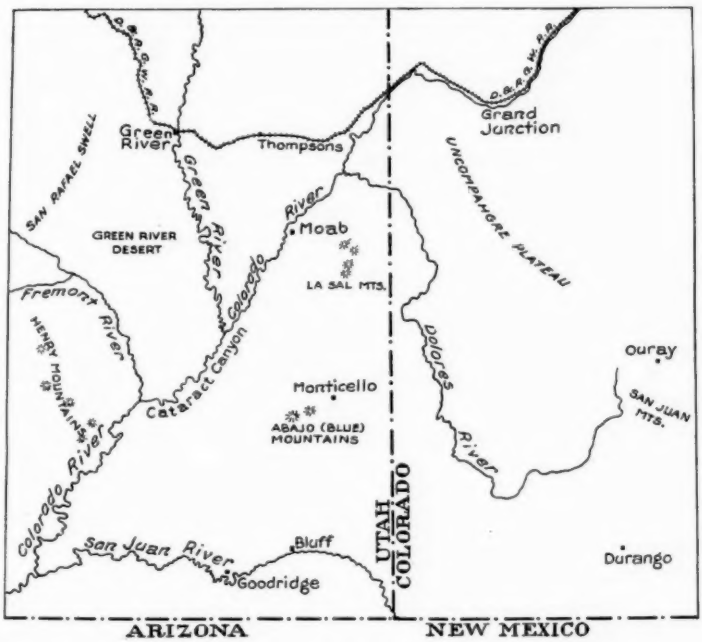

FIG. 1.—Index map of southeastern Utah and southwestern Colorado

Boulder 4. *Spirifer centronatus* or *S. rockymontanus.*

Boulder 5. *Triplophyllum* sp., *Rhipidomella* aff. *R. pulchella, Spirifer* aff. *S. centronatus, Composita?* sp.

Boulder 6. *Triplophyllum* sp., *Fenestella*, several species, *Schizophoria* sp., *Productus ovatus, P.* aff. *P. fernglenensis, Productella* aff. *P. concentrica, Camarotoechia* sp., *Girtyella?* sp., *Spirifer centronatus, Spirifer*, sp., *Delthyris novamexicana?*

Concerning these fossils, Girty says:

Although much of the material is fragmentary and all of it imperfect and

scanty, I am satisfied that we have here a fauna of early Mississippian age, and that these boulders had their source in the Madison limestone, the Ouray limestone, or the Lake Valley limestone—to use the names of correlated formations. This opinion can be supported only as regards three of the boulders [Nos. 1, 2, 6], though the probabilities point to all six of them being of the same age. The doubtful three might be Pennsylvanian but hardly Devonian.

PENNSYLVANIAN ROCKS

Hermosa formation.—The part of the Hermosa formation exposed in the Moab region consists at most places of dove-gray to brownish thick-bedded limestone interbedded with light greenish-gray sandstone, massive and cross-bedded. Minor beds of blue-green limestone, gray calcareous shales, and thin-bedded limestone are also present and rarely red sandstone and arkose. The principal areas of exposure are the inner canyons of Colorado River and the folded areas such as Moab Valley. The greatest thickness seen, 800 feet, is near the junction of Green and Colorado rivers. The top of the formation is placed arbitrarily where the thick limestones give way to dominant red beds though there is no evidence of any interruption of sedimentation at the horizon at any locality seen by the writers.

In the San Juan Mountains[1] limestone preponderates over other rocks in the lower part of the formation, and the total thickness is about 2,000 feet. In the wells in the Moab region the interval 1,000 to 1,800 feet below the top of the formation shows much more limestone than the part that crops out at the surface, and at 1,600 to 1,800 feet below the top of the formation, a change takes place in the lithology, from sandstone and limestone to considerable thicknesses of shale, gypsum, and salt. This latter set of materials extends as far downward as drilling has been carried —nearly 3,000 feet below the limestones. If thicknesses are comparable in the San Juan Mountains and eastern Utah, it is at least possible that little of the pre-limestone sequence shown in the wells is of Hermosa age. It is of course also possible that local differences in sedimentation enter and that the beds of Hermosa age in the two areas are not comparable. It seems likely, furthermore, that plastic movements of the salt and gypsum content of the sequence of rocks have modified the original arrangement at the points where wells have been drilled. It does not seem to the writers, however, that the Hermosa age of the shale, salt, and gypsum beds below the limestone is yet established. The locality cited by Harrison,[2] near Redmond, Utah, a few miles east of Salina, is in all probability

[1] Whitman Cross, Rico Folio, *U. S. Geol. Survey Geol. Atlas*, Folio 130 (1905), p. 3.

[2] T. S. Harrison, *op. cit.*, p. 112.

of Upper Jurassic age and equivalent to some part of the San Rafael group. It has no bearing on the age of the deposits of the Moab region.

From the Hermosa formation along and near Colorado River a number of collections of fossils were made. These have been examined by Girty, who reports the following species as present in these collections and not occurring in collections made higher in the section.

Fusulina secalica, Campophyllum torquium, C. kansasense, Lophophyllum profundum, Syringopora multattenuata, Echinocrinus coloradoensis, Delocrinus aff. *D. texanus, Erisocrinus propinquus, Cyclotrypa barberi, Thamniscus* aff. *T. guadalupensis, Rhipidomella carbonaria, Derbya crassa, Chonetes granulifer, C. geinitzianus, Productus semireticulatus, P.* aff. *P. guadalupensis, Pustula semipunctata, P.* aff. *P. porrecta, Pustula* n. sp., *Marginifera splendens, M. nebraskensis, M. wabashensis, Rhynchopora* aff. *R. taylori, R. illinoisensis, Pugnoides osagensis, Dielasma* sp., *Spiriferina* aff. *S. gonionotus, Squamularia perplexa, S.* aff. *S. guadalupensis, Brachythyris* n. sp., *Cliothyridina orbicularis, Hustedia mormoni, Platyceras occidentale?, Griffithides* sp.

The fauna, in comparison with that of the overlying beds, is notable for the abundance of brachiopods and the relative scarcity of mollusks. Some species other than those named above do continue on into the Rico formation, though the aspect of the higher fauna is distinct in spite of the common species. Among these common species are:

Stenopora carbonaria, Rhombopora lepidodendroides, Derbya bennetti, Productus cora, P. pertenuis, Pustula nebraskensis, P. symmetrica, Spirifer triplicatus, Spiriferina kentuckyensis, Composita subtilita, Edmondia gibbosa, Allerisma terminale, Pinna peracuta, Acanthopecten carboniferus, Schizostoma catilloides.

The fauna supports a correlation of the Hermosa formation of the Moab region with that of the type area in the San Juan Mountains and with the lower 1,200 feet of the Goodridge formation of the San Juan Valley, as described by Woodruff.[1] In the Grand Canyon region a similar Pennsylvanian fauna is known in beds that form the upper part of the Redwall limestone as originally defined by Gilbert[2] and accepted by Darton[3] and the lower part of the Supai formation as defined by Noble[4] and as now used by the United States Geological Survey. Whether the

[1] E. G. Woodruff, "Geology of the San Juan Oil Field, Utah," *U. S. Geol. Survey Bull. 471* (1912), pp. 81–85.

[2] G. K. Gilbert, *U. S. Geog. and Geol. Surveys W. 100th Mer. Rept.*, Vol. 3 (1875), pp. 161, 162, 177, 178, 185.

[3] N. H. Darton, "A Reconnaissance of Parts of Northwestern New Mexico and Northern Arizona," *U. S. Geol. Survey Bull. 435* (1910), p. 22.

[4] L. F. Noble, "A Section of the Paleozoic Formations of the Grand Canyon at the Bass Trail," *U. S. Geol. Survey Prof. Paper 131* (1923), pp. 54–64.

upper part of the Supai of Noble is Pennsylvanian or Permian has not been determined on a paleontologic basis.

PERMIAN ROCKS

Rico formation.—The Rico formation, conformable upon the Hermosa formation, is essentially sandy, arkosic, maroon to dark purplish-red beds with included dove-gray, greenish-gray, or reddish limestones. Over much of the Colorado Valley below Moab the top of the Rico has been placed above a relatively thick limestone forming a conspicuous bench and called by many geologists the "Shafer limestone"—a name already applied to a Devonian limestone in New York and therefore used in this paper only in a quotational sense. At other localities the limestones are inconspicuous and the boundary between the Rico formation and the overlying Cutler red beds must be placed arbitrarily, perhaps most conveniently at the highest fossiliferous beds known in the Rico-Cutler sequence. The principal areas of exposure are, like those of the Hermosa formation, the inner canyons of Colorado River and the folded areas such as Moab Valley. The thickness where the so-called "Shafer limestone" is present is consistently between 500 and 600 feet. In Moab Valley the highest fossiliferous bed, also the highest limestone, is a thin bed 340 feet above the Hermosa, but it is probably not at the horizon of the "Shafer limestone."

From the Rico formation along and near Colorado River a number of collections of fossils were made. In these Girty found the following species present which do not also occur in the collections from the Hermosa formation:

Edmondia glabra, E. aspinwallensis, Chaenomya? sp., *Sanguinolites costatus, S.* n. sp., *Nucula levatiformis, Yoldia* sp., *Leda arata, Parallelodon* sp., *Pleurophorus* aff. *P. subcostatus, Schizodus curtus, S. curtiformis, S. meekianus, S. compressus, S. wheeleri, Deltopecten occidentalis, Aviculipecten* n. sp., *Myalina subquadrata, M. wyomingensis, Pteria longa, Monopteria marian, M. polita, M.* n. sp., *Posidoniella?* sp., *Lima* sp., *Pseudomonotis equistriata, P. kansasensis, P. sublevis, Astartella subquadrata, Plagioglypta canna, Bellerophon crassus, Patellostium* sp., *Pharkidonotus percarinatus, P. percarinatus* var. *tricarinatus, Bucanopsis meekana, B.* aff. *B. bella, Pleurotomaria* sp., *Euconospira? excelsa, Naticopsis deformis, N.* (*Diaphorostoma*) *remex, Aclisina* sp., *Sphaerodoma hallana, Bulimorpha chrysalis, Orthoceras* sp., *Pseudorthoceras knoxense, Griffithides major.*

Girty says of the fossils:

Few paleontologists would question the Pennsylvanian age of the older fauna [Hermosa] in these collections. The only discussion that demands atten-

tion is the Permian age of the later fauna [Rico]. The Pennsylvanian and Permian faunas are in strong contrast and the change of facies shown by their stratigraphic occurrence is abrupt, yet the character of this change is such as might readily be a response to a change in local conditions of environment as well as something more widespread and fundamental. The change, namely, consists in this: The brachiopods from being varied and abundant become few and scarce, and the molluscs from being few and scarce become varied and abundant. The few brachiopods of the later fauna are but survivals from the earlier, while the scanty earlier fauna of pelecypods and gastropods also seems to survive but to be augmented in the later fauna by a large number of species not found in the earlier. In a broad way the same contrast is shown by the Pennsylvanian and Permian faunas of Kansas, only in Kansas the transition is less abrupt. Nearer at hand the same contrast is shown by the Hermosa and Rico of Colorado, though in Colorado the age assignments are on a tentative basis. In my judgment the later faunas in the region under discussion may be assigned to the Permian for the following reasons, though the assignment should be recognized as provisional:

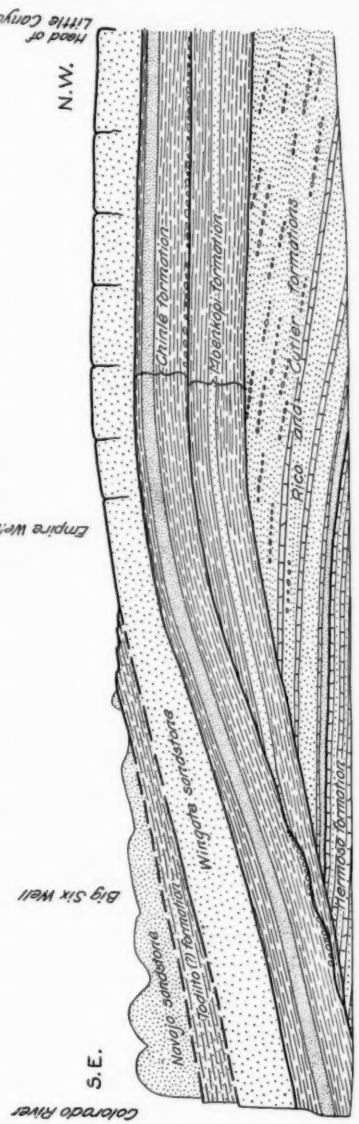

FIG. 2.—Diagrammatic section showing stratigraphic and structural relations in the southwest wall of Moab Valley northwest of Moab, Utah.

1. The latter fauna marks a change from the earlier that is at once pronounced and abrupt.

2. The change is in a broad way comparable to the transition that marks the passage from Pennsylvanian to Permian in the Kansas section.

3. These faunas are decisively of eastern or Kansas type.

4. The classification seems to conform to that recognized, if only tentatively, in the near by San Juan section of Colorado.

The change from the Hermosa fauna to the Rico fauna is sharp at all localities where collections were made to determine it, sharper, in fact, than one might expect considering the nature of the boundary. At many localities there is an accompanying change in lithology though at other places the change of fauna is not strictly coincident with the change in lithology. The species present afford a correlation with the upper 350 feet of the typical Goodridge formation and with the Rico of the San Juan Mountains. The fauna is allied to the Permian faunas of Kansas, and is separated sharply from the fauna of the Kaibab limestone of the Grand Canyon region and its allies. The writers believe the beds here designated Rico to contain, in addition to uppermost Goodridge, the equivalent of the Supai (?) formation of Cataract Canyon and the San Juan River Valley,[1] though the latter has yielded no fossils. In the Grand Canyon region no fauna comparable to the Rico fauna is known, though it is probable that its time interval is represented in the Supai or Hermit formations by unfossiliferous beds.

Cutler formation.—Conformably upon the Rico formation rests the Cutler formation, a series of maroon to dark purplish-red cross-bedded sandstones, arkoses, and arkosic conglomerates that form cliffs and pillars or steep slopes. In a broad view the bedding is regular but in detail it is irregular. Minor beds of red-brown or chocolate-colored sandstone are present also. The conglomerates contain pebbles of quartz, feldspar, granite, quartzite, and a dark crystalline rock, which increase in size eastward. On Colorado River below the Cane Creek dome, thin layers of gray-white sandstone appear in the series of red beds. These layers thicken and become more numerous downstream (southwestward) until at the junction with the Green they make up a large part of the section. An especially notable tongue of white sandstone forms the top of the Cutler formation over a large area north of Colorado River and westward across Green River, making a pronounced bench long known to the local residents as the White Rim. It has been interpreted by many geologists as

[1] C. R. Longwell and others, "Rock Formations in the Colorado Plateau of Southeastern Utah and Northern Arizona," *U. S. Geol. Survey Prof. Paper 132* (1923), p. 7.

equivalent to the De Chelly(?) sandstone[1] of lower Cataract Canyon and the San Juan Valley. This De Chelly(?) sandstone was not seen in the outcrops south of Colorado River above its junction with the Green, and on the north side thins out completely between Shafer dome and Cane Creek dome. Another notable layer of white sandstone, the basal member of the Cutler at the junction, is the rim-rock of the inner canyon at that place, but upstream along the Colorado it gradually becomes red and is lost in the sequence of red beds. This layer has been considered to be the eastward-thinning wedge of the Coconino of Cataract Canyon, though it is only one of a number of similar wedges. The passage by intertonguing from red Cutler beds to light-colored Coconino may be seen especially well from the southernmost point of the White Rim between Green and Colorado Rivers.

The principal areas of exposure of the Cutler formation are a wide, deeply dissected belt on each side of Colorado River above the inner canyon and some miles along Green River above the mouth, and the folded areas like Moab Valley. The beds identified by Cross[2] as Permian(?) (presumably Cutler) at the Big Bend of Colorado River, 12 miles above Moab, are, as shown below, not Cutler but an unusual development of Shinarump conglomerate.

The thickness of the Cutler formation is variable, due in large part to the succeeding unconformity. In Moab Valley it is cut out southward by the overlying Moenkopi formation but northward attains a thickness of about 600 feet. Along Colorado River it is 400 to 600 feet thick. The De Chelly(?) sandstone near the junction of the Green and Colorado is 75 to 100 feet thick and the heavy basal ledge about 200 feet.

The lithologic characteristics and relation to the Rico formation support so strongly a correlation of the Cutler formation of the Moab region with that of the type area in the San Juan Mountains that the use of the name seems fully justified in spite of the lack of paleontologic evidence and discontinuity of outcrops. There is also no doubt, in the opinions of the writers, that the greater part of the red Cutler of the Moab region grades directly westward and southward into the large light-colored sandstone body of Cataract Canyon commonly designated Coconino sandstone[3] and is essentially contemporaneous with it; that the upper part of

[1] C. R. Longwell and others, *op. cit.*, p. 9.

[2] Whitman Cross, "Stratigraphic Results of a Reconnaissance in Western Colorado and Utah", *Jour. Geol.*, Vol. 15 (1907), pp. 654, 659, 667.

[3] C. R. Longwell and others, *op. cit.*, p. 8; T. S. Harrison, *op. cit.*, p. 115; H. W. C. Prommel and H. E. Crum, *op. cit.*

the Cutler includes also equivalents of the beds usually placed in the lower part of the Moenkopi formation and De Chelly(?) sandstone member in the same region and in the San Juan Valley. The Cutler is essentially equivalent, in all probability, to the Coconino sandstone of San Rafael Swell,[1] though the thin Kaibab limestone resting upon the sandstone has no counterpart in the Moab region and exact identity of the Cutler and the Coconino cannot be definitely proved. The equivalence of the Cutler, through the Coconino sandstone, etc., of southeastern Utah, to formations in the Grand Canyon region can be determined at the present time in only the most general way. The Kaibab limestone of San Rafael Swell is very late Kaibab[2] and is probably close in age to the De Chelly(?), the top of the Cutler in the Cataract Canyon–Moab region thus affording an upper limit in correlation. The Pennsylvanian beds of the Hermosa and lower part of the Supai (originally included in Redwall) afford an approximate lower limit. Correlation of the intermediate beds is guesswork, though the Cutler seems likely to be the time equivalent of typical Kaibab, typical Coconino, and some part of the Hermit or typical Supai.

CONTACT OF PERMIAN AND TRIASSIC

The contact between the Cutler formation and the overlying Moenkopi formation at most places is sharp though not notably sinuous. The contrast between the red-brown or chocolate-colored, thin and evenly-bedded, and soft, slope-forming strata of the Moenkopi and the deep-red to purple, arkosic, cliff- and pillar-forming beds of the Cutler is marked. In Moab Valley there is, in addition to the lithologic contrast, an angular discordance of as much as 4 degrees, and the base of the Moenkopi rests in succession on strata from a horizon below the top of the Hermosa to a horizon in the Cutler 1,000 feet above the top of the Hermosa. In Castle Creek Valley, northeast of Moab, the distinction between Cutler and Moenkopi does not seem as clear as at other localities. The base of the Moenkopi over all of southern Utah and northern Arizona is a horizon of marked unconformity and the Moab region appears to offer no exception.

LOWER TRIASSIC

Moenkopi formation.—The Moenkopi formation consists in general of red-brown or chocolate-colored, thin-bedded, fine-grained, ripple-marked sandstone and sandy shale. Frequently a middle zone of harder beds

[1] James Gilluly and J. B. Reeside, Jr., "Sedimentary Rocks of San Rafael Swell and Some Adjacent Areas in Eastern Utah," *U. S. Geol. Survey Prof. Paper.* (In press.)

[2] *Ibid.*

stands out in exposures as a cliff or rough slope with a smoother slope above and below. The bedding is fine and very even. Veins and thin sheets of gypsum are not uncommon. In Green River Valley the upper half of the formation, with the exception of the top 40 feet, changes northward within a couple of miles from red to a light greenish-gray, weathering creamy-white, but in a short distance farther northward changes again abruptly to red. Near the base of this light zone a fossiliferous, dark-gray impure limestone some 320 feet above the base of the formation yielded marine fossils like those in the similar unit named in San Rafael Swell the Sinbad limestone member.[1] It is believed that the lithology, contained fossils, and stratigraphic position justify the use of the member name in Green River Valley.

The principal areas of exposure are the bluffs bordering the valley of Green River and the valley of the Colorado below Moab, Moab Valley, Castle Creek Valley, and along Colorado River near Castle Creek. Moenkopi is absent in the valleys to the southeast, such as Big Indian Valley and Paradox Valley.

The Moenkopi formation thickens along Colorado River from about 400 feet near Cane Creek to about 600 feet on Green River—an increase which seems to continue westward to San Rafael Swell, where a thickness of 800 feet is reported.[2] In Moab Valley the formation is cut out near the exit of Colorado River by the overlying Upper Triassic but appears near the Big Six Well and forms there 35 feet of the Permian (?) noted by Cross[3] in 1907. It thickens rapidly northward and in 3 miles attains a maximum thickness of 450 feet. About 4 miles farther north, beyond the mouth of Sevenmile Canyon, it is again very much reduced. In Castle Creek Valley the thickness ranges from a vanishing edge to 500 feet.

Fossils from the Sinbad limestone member in Green River Valley, Girty identified as *Lingula* sp., *Monotis?* aff. *M. thaynesiana*, viviparoid gastropods, *Meekoceras?* sp. Concerning these fossils Girty says:

> All the fossils are preserved as molds with their smaller characters considerably obscured. The gastropod fauna is varied and all the species are probably new. Many of these shells show a marked superficial resemblance to *Viviparus*, but *Viviparus* is a fresh-water genus and this fauna, one can scarcely doubt, is marine. At all events, though the paleontologic evidence can be stated only in such general terms, there is no doubt whatever that the horizon is Lower Triassic.

The marine fauna in the Moenkopi formation of Green River Valley establishes its age as Lower Triassic and as belonging, at least in part, to

[1] *Ibid.* [2] *Ibid.* [3] Whitman Cross, *op. cit.*, p. 669.

the world-wide *Meekoceras* zone. It permits a correlation westward and southwestward with the Moenkopi of San Rafael Swell, of central and western southern Utah, and of northwestern Arizona, and through the latter localities with the type area. Northeastward from Green River the exposures are continuous from Green River almost to Moab and leave no doubt that the unfossiliferous beds near Moab are the direct equivalent. There seems also to be little doubt that the upper, post–De Chelly (?), part of the so-called Moenkopi of southeastern Utah[1] alone is true Moenkopi, and that the De Chelly (?) sandstone and underlying so-called "lower Moenkopi" are Permian. Longwell found in Cataract Canyon an unconformity beneath his "lower Moenkopi," and another between his "upper Moenkopi" and the De Chelly (?) sandstone. In the light of the data available in the Moab region it seems likely that the upper unconformity will prove to be the more important of the two. In San Juan Valley no unconformity was recognized beneath the "lower Moenkopi." Gypsiferous beds on the northern margin of the valley at the town of Moab which have been considered by Cross[2] and others to be Moenkopi are Chinle. Similar beds on the south side of the valley are at least in part Chinle as shown by their fossils.

CONTACT OF LOWER AND UPPER (?) TRIASSIC

Over a large area along Colorado River the contact between Moenkopi and overlying beds is sharp and somewhat, though not strikingly, sinuous. In Moab Valley the Moenkopi is cut out near Colorado River and is greatly reduced near Sevenmile Canyon by an unconformity. In Castle Creek Valley a similar relation exists. In Big Indian Valley and apparently at all localities eastward into Colorado no Moenkopi is present. The Shinarump conglomerate has been accepted by all as unconformable on the preceding beds over all of southern Utah and northern Arizona. Upper Triassic (Chinle and Dolores), where Shinarump conglomerate is not recognized, is likewise accepted as unconformable on preceding beds. The hiatus above the Moenkopi in the Moab region therefore forms part of a widespread interruption in sedimentation, possibly representing all of Middle Triassic time.

UPPER TRIASSIC (?)

Shinarump conglomerate.—The Shinarump conglomerate, usually a coarse quartzose sandstone containing lenses of quartz pebbles and some cherts, varies in color from gray-white through rusty brown to nearly

[1] C. R. Longwell and others, *op. cit.*, p. 9.

[2] Whitman Cross, *op. cit.*, p. 654.

black. It contains at many places lenses of sandy shale and chunks of silicified wood and is extremely irregular in bedding. It may be recog-

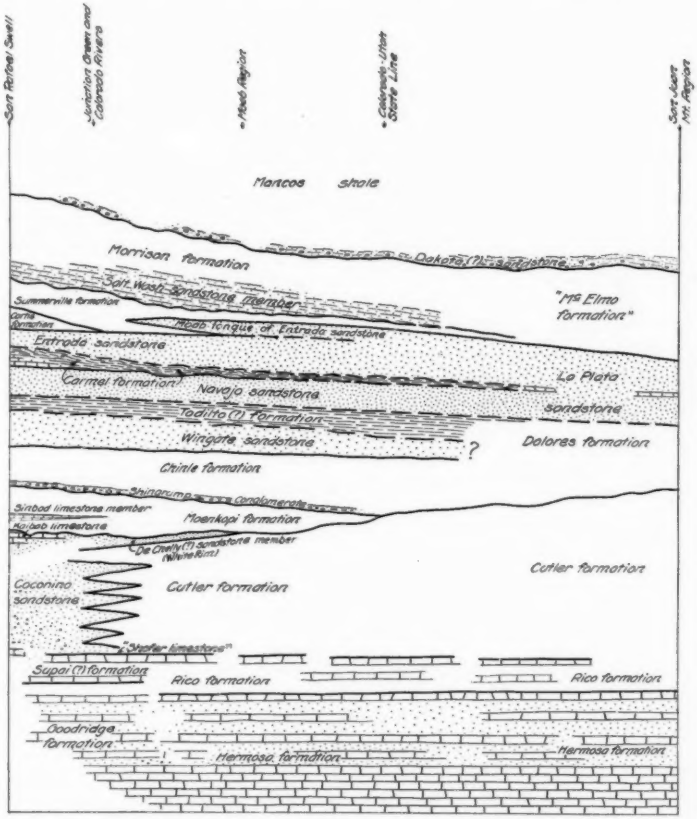

FIG. 3.—Diagrammatic section showing stratigraphic relations in the area between San Rafael Swell, Utah, and San Juan Mountains, Colorado.

nized along Colorado River at and below the Cane Creek dome, but at Moab only thin isolated lenses of whitish quartz grit and fine conglomerate in the lower part of the Chinle formation suggest its presence. Upstream above Moab as far as the Big Bend, about 10 miles above Moab, only the thin whitish lenses occur in the lower part of what would otherwise be a

normal Chinle lithology. There the Shinarump suddenly takes on an individuality again and forms the striking series of topset and foreset beds which appear unconformable and have been so interpreted since Cross[1] noted them and figured them as Permian (?) (presumably Cutler). The rocks are largely dark-weathering conglomeratic sandstone, with pebbles nearly all of quartz and attaining a diameter of more than an inch, though there is also a considerable body of greenish-gray limy shale. The base of this locally thickened Shinarump is not exposed at the Big Bend, but as the unit rises upstream, the underlying Moenkopi comes into view and renders unquestionable the identity of the unusual beds as Shinarump. Farther southeast and east no beds of siliceous conglomerate of the type of the Shinarump are known, and it has been supposed by many that the conglomerates of limestone pellets and saurian bones—the "Saurian conglomerate" of Cross and others—may represent the Shinarump. The presence of such limestone conglomerates in sections where an unquestioned Shinarump conglomerate is also present or the occurrence of a number of them scattered throughout the thickness of the Chinle or Dolores makes it unlikely that any one of them has a genetic relation to the Shinarump and is a real equivalent. It seems more convenient to interpret the data now available as showing the Shinarump to lose its identity eastward by merging into the lower part of the Dolores formation of the San Juan Mountains.

The Shinarump locally exceeds 100 feet in thickness but is generally much thinner. At one locality it is 200 feet.

There seems to be no valid reason for doubting the essential equivalence of the Shinarump conglomerate of the Moab region with that of southern Utah and northern Arizona, for the lithology and stratigraphic position are identical. The writers believe that the Shinarump is so intimately connected with the overlying Chinle formation that it does not differ from it in age enough to deserve separation. However, up to the present time so few significant organic remains have been found that the writers have retained the usual query on the assignment to the Upper Triassic.

UPPER TRIASSIC

Chinle formation.—The Chinle formation is an assemblage of red and green sandy mudstone or sandstone, some layers of the red sandstone weathering almost black; conglomerates of quartz and limestone pebbles, and conglomerates of pellets of gray limy mud, all lenticular and con-

[1] *Ibid.*

taining saurian teeth and bones. Mudstones are important locally and at some places gypsum appears. The formation in general is irregularly bedded, though some of the sandstones persist over considerable distances along the outcrop. Such a layer near the middle of the formation is strikingly shown in Moab Valley where it forms a marked ledge descending toward Colorado River from the northwest. This layer has been interpreted as Shinarump conglomerate[1] and as basal Vermilion Cliff (Wingate).[2]

The principal occurrences of the Chinle formation are in the bluffs bordering the valleys of Colorado and Green Rivers and around the folded areas such as Moab Valley.

The thickness is variable. In Moab Valley it decreases from about 450 feet at Colorado River northwestward to 212 feet at the Empire well—a distance of 3 miles, the thinning being due chiefly to loss of beds at the top though also to irregularities at the base. Along Colorado River the formation is 350 to 750 feet thick. In Big Indian Valley it is 460 feet thick; in Castle Creek Valley, 430 feet.

The Chinle formation in the Moab region has yielded bones of vertebrates and fresh-water invertebrates which show it to be of Upper Triassic age and equivalent to some part of the Dolores formation of the San Juan Mountains and to the Chinle of southern Utah and northern Arizona, a correlation amply supported by the lithologic characteristics and stratigraphic position.

CONTACT OF TRIASSIC AND JURASSIC (?)

The contact of the soft, slope-forming Chinle formation with the vertical cliffs of Wingate sandstone is the most conspicuous lithologic boundary in the region. In close view, however, it is at many places not an impressive unconformity. There are locally beds near the top of the Chinle which closely resemble the Wingate and make the exact location of the boundary debatable, though at other places it is sharply defined. In Moab Valley the upper member of the Chinle decreases in about 3 miles from approximately 200 feet to 50 feet, and the base of the Wingate is somewhat sinuous and contains locally a conglomerate of small chert pebbles. It has been the general opinion of students of the Plateau country that the Wingate is unconformable on the Chinle, an interpretation accepted for the Moab region chiefly on the evidence of Moab Valley.

[1] T. S. Harrison, *op. cit.*, p. 118, Fig. 7; H. W. C. Prommel and H. E. Crum, *op. cit.*

[2] Whitman Cross, *op. cit.*, p. 669.

JURASSIC (?) ROCKS

For the group of rocks including the Wingate sandstone, Todilto (?) formation, and Navajo sandstone, long known as the La Plata group, Gregory and Moore[1] have proposed the name Glen Canyon group, since it is now known that the La Plata sandstone of the San Juan Mountains does not include rocks older than Navajo. The formations are closely related in lithologic features and the boundaries between them are purely arbitrary. The only fossils now known are of little value for determination of age. The group follows Upper Triassic beds, is succeeded by Upper Jurassic beds, and might therefore include part of the Upper Triassic, Lower and Middle Jurassic, and part of the Upper Jurassic. It seems best for the present to assign it with doubt to the Jurassic.

It has been thought by some writers that the base of the Navajo is an important break in sedimentation because of the evident unconformity at the base of the La Plata sandstone in the San Juan Mountains, though there is little support for such an interpretation in the Moab region and other regions to the west and south.

Wingate sandstone.—The massive, much cross-bedded, gray or tan to brownish-red, medium-grained Wingate sandstone is in part clearly water-laid and in part possibly aeolian. The outcrops, characterized by vertically jointed cliff-faces and much desert varnish, are widely distributed but are especially prominent in the rims of Colorado and Green River valleys and in the folded areas like Moab Valley. The thickness is 300 to 350 feet over the area here described. There seems to be no doubt that the Wingate sandstone in the Moab region is identical with that so called by Gregory[2] and others in southern Utah and northwestern Arizona. Whether it is strictly equivalent to the Wingate sandstone of eastern Arizona and northwestern New Mexico (the type region) is debatable. Wingate as applied by Emery[3] in Green River Desert is the whole Glen Canyon group.[4] Eastward from the Moab region the Wingate sandstone appears to pass into the upper part of the Dolores formation.

Todilto (?) formation.—The Todilto (?) formation, chiefly irregularly bedded sandstone, red near base, buff and lavender at top, with sub-

[1] H. E. Gregory and R. C. Moore, "The Kaiparowits Region." (Awaiting publication.)

[2] H. E. Gregory, "Geology of the Navajo Country," *U. S. Geol. Survey Prof. Paper 93* (1917), p. 53.

[3] W. B. Emery, "Green River Desert Section," *Am. Jour. Sci.*, Vol. 46 (1918), pp. 564–68.

[4] James Gilluly and J. B. Reeside, Jr., *op. cit.*

ordinate sandy shale and beds of limestone, forms a bench or thin-bedded zone between the associated massive sandstone formations. Its thickness is usually 250 feet. The Todilto (?) formation near Cane Springs yielded several simple species of *Unio* much like forms occurring both below, in the Chinle formation, and above, in the Morrison formation, and also large stems of an undetermined plant, possibly a fern. These fossils show the formation to be of fresh-water origin and not marine, as suggested by Harrison.[1] The Todilto (?) formation of the Moab region is the middle zone of the Wingate of Emery[2] in Green River Desert, and seems undoubtedly to be equivalent to the Todilto formation of Gregory and others as the name has been used in southern Utah and northwestern Arizona. That it is the equivalent of the typical Todilto limestone of eastern Arizona and northwestern New Mexico is very doubtful. The Todilto (?) formation appears to pass eastward into the uppermost part of the Dolores formation of Colorado.

Navajo sandstone.—The Navajo sandstone is gray-white to light-brown, much cross-bedded, and medium-grained. Much of the rock is possibly aeolian in origin though parts are undoubtedly water-laid. A few gray limestone lenses occur here and there but are not an important part of the formation. The characteristic outcrops, cliffs ending above in rounded domelike forms, are extensive in the flat areas between the canyons by which the region is drained. The formation in the Moab region is undoubtedly the equivalent of the typical Navajo sandstone of the Glen Canyon district. Eastward it becomes the lower part of the typical La Plata sandstone of the San Juan Mountains, as pointed out by Lee and Boyer.[3] As used here the name Navajo includes only the "Lower Navajo" of Prommel and Harrison[4] and the upper part of the Wingate of Emery[5] in Green River Desert.

CONTACT OF JURASSIC (?) AND UPPER JURASSIC

This boundary is sharply defined over a very large area and at places seems to be sinuous, but that it is an important erosion plane has not been demonstrated beyond doubt. Farther west the change from massive cross-bedded sandstone to fossiliferous marine limestone is striking. Eastward the plane of contact is in the midst of the La Plata sandstone.

[1] T. S. Harrison, *op. cit.*, p. 115

[2] W. E. Emery, *op. cit.*, p. 565; James Gilluly and J. B. Reeside, Jr., *op. cit.*

[3] W. T. Lee and W. W. Boyer, *U. S. Dept. Interior Memo. for the Press* (March 30, 1926).

[4] H. W. C. Prommel, *op. cit.*, p. 387; T. S. Harrison, *op. cit.*, p. 115.

[5] W. B. Emery, *op. cit.*, pp. 564–68; James Gilluly and J. B. Reeside, Jr., *op. cit.*

UPPER JURASSIC ROCKS

For the group of rocks including, in ascending order, the Carmel formation, the Entrada sandstone, the Curtis formation, and the Summerville formation Gilluly and Reeside[1] have proposed the name San Rafael group. The Carmel formation and the Curtis formation contain, in San Rafael Swell, Upper Jurassic marine fossils and the Curtis formation passes without break into the Summerville formation, thus fixing the age of the group as Upper Jurassic. The Curtis formation thins eastward from San Rafael Swell and is not recognized in the Moab region, but the other formations have been traced in by Gilluly and Reeside and the names are applied with confidence.

Carmel formation.—The Carmel formation consists of red sandstone, minor red sandy shale, and still less limestone. It is thin-bedded, usually crinkled on a large scale, and contains minor unconformities which truncate the crinklings at places. It varies much in thickness—at places it is only 30 to 40 feet and at others exceeding 100 feet. On the northeast side of Moab Valley at the Dugway, the red Carmel beds are completely replaced for a short distance by rocks like the overlying Entrada. The Carmel formation is relatively soft and retreats to form a widespread bench between Navajo and Entrada sandstones. It becomes the middle part of the La Plata of the San Juan Mountains and is the "Middle Navajo" of Prommel and Harrison[2] and the Todilto of Emery[3] in Green River Desert. The Carmel formation has yielded no fossils in the Moab region.

Entrada sandstone.—The Entrada sandstone, like the Navajo, outcrops widely on the stream divides, forms cliffs, and is massive, much cross-bedded, and medium-grained, but has more pink or orange coloring. It is 300 to 400 feet thick but thins eastward and becomes the upper La Plata of the San Juan Mountains. It is the "Upper Navajo" of Prommel and Harrison[4] and the lower part of the Navajo of Emery[5] in Green River Desert. A persistent, somewhat lighter-colored, upper bed of the Entrada was called Moab sandstone by the late Dr. W. T. Lee in an unpublished report. This bed is a tongue that thins westward and in the western part of the area is separated from the remainder of the formation by a westward-thickening wedge of Summerville beds. It is proposed here to call it the "Moab tongue of the Entrada sandstone." It is typically exposed in

[1] James Gilluly and J. B. Reeside, Jr., *op. cit.*

[2] H. W. C. Prommel, *op. cit.*, p. 387; T. S. Harrison, *op. cit.*, p. 115.

[3] W. B. Emery, *op. cit.*, pp. 568–70; James Gilluly and J. B. Reeside, Jr., *op. cit.*

[4] H. W. C. Prommel, *op. cit.*, p. 387; T. S. Harrison, *op. cit.*, p. 115.

[5] W. B. Emery, *op. cit.*, pp. 570–72; James Gilluly and J. B. Reeside, Jr., *op. cit.*

the Moab Valley. The tongue eventually thins out completely and the Summerville lithology extends upward without break from the plane which is in the east the base of the Moab tongue. Prommel[1] recognized this unit as an upper unconformable part of his "Upper Navajo."

No fossils are known from the Entrada sandstone.

Summerville formation.—Summerville formation consists of red to chocolate-colored, very thin bedded, shaly sandstone with some beds of

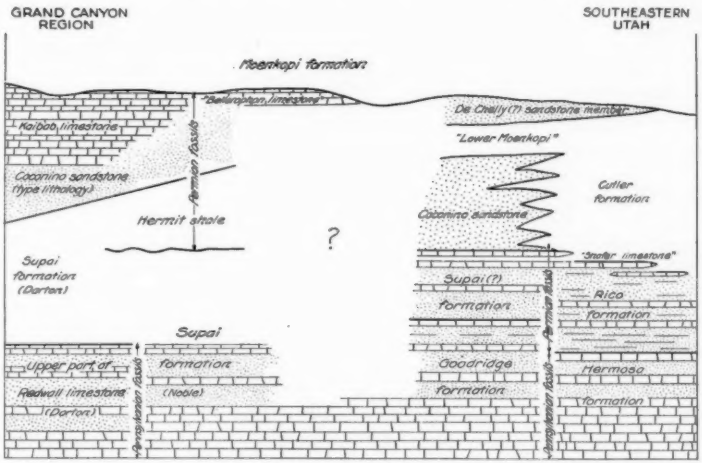

FIG. 4.—Diagrammatic section showing stratigraphic relations in the area between the Grand Canyon region, Arizona, and the Moab region, Utah. Redwall is now restricted by the U. S. Geological Survey to massive limestone of Mississippian age not shown in this diagram.

limestone and much silica in crusts and large nodular aggregates. It is relatively soft and its outcrop is usually a slope beneath the overlying sandstones. The formation in the Moab region is from 50 to 100 feet thick. It is the upper part of the Navajo of Emery and the basal part of the "McElmo" of Cross and other students of the region. The Summerville has not yielded fossils.

CONTACT OF JURASSIC AND CRETACEOUS (?)

The contact of the Summerville and the overlying Salt Wash member of the Morrison formation is unconformable, an irregular erosion surface.

[1] H. W. C. Prommel, *op. cit.*, p. 387.

There are, however, other similar irregularities higher in the section, and it is debatable how important the unconformity at the base of the Salt Wash member may be in this region. In San Rafael Swell the top of the Summerville formation is a conspicuous plane of discordance.[1]

CRETACEOUS (?) ROCKS

Morrison formation.—The Morrison formation, as interpreted here, contains in the lower part the Salt Wash sandstone member—thick beds of gray-white sandstone separated by red shaly sandstone; and in the upper part, a member of variegated chocolate-colored, red, gray, green, and purple mudstone and shales and interbedded minor gray sandstone and conglomerates with pebbles of siliceous rocks, in part silicified. The Salt Wash member is perhaps 300 feet thick near Moab and thins westward; the upper member is about 250 feet thick. Westward the formation as a whole attains a thickness of 800 feet. Both members contain dinosaur bones, silicified wood, and fresh-water shells, and both are irregularly bedded. The formation forms the greater part of the "McElmo formation" of Cross and other writers.

UPPER CRETACEOUS ROCKS

Dakota (?) sandstone.—The Dakota (?) sandstone is a variable gray-to-brown sandstone and conglomerate of siliceous pebbles. It is undoubtedly at many localities of Upper Cretaceous age only, though at some localities in the regions to the east and south, plant fossils suggest that it may include also some older beds. Relations to beds of accepted Dakota age are uncertain and the name is therefore applied with query.

TENTATIVE HISTORY OF THE MOAB REGION

There is very little usable information on the pre-Pennsylvanian history of the Moab area. The occurrence of a coarse conglomerate containing, so far as now known, only boulders of lower Mississippian rocks at a considerable distance from any outcrop of Mississippian, and forming a type of rock not known elsewhere, suggests the possibility that at some time between lower Mississippian and Pennsylvanian times folding may have exposed the lower Mississippian in the Moab region and permitted the formation of the boulder bed. Later events in the history of the region may then have combined by chance to bring it to the surface at only one point. Elsewhere it is still concealed beneath younger beds, if present at all.

The Pennsylvanian, if the greater part of the salt and gypsum found

[1] James Gilluly and J. B. Reeside, Jr., *op. cit.*

underground is not Pennsylvanian, appears to have been a time of normal marine conditions, the earlier sediments being chiefly limestone and the later, limestone with much sandstone (Hermosa). These pass into interbedded red sediments and marine limestone (Rico), here accepted as of Permian age, whose faunal relations are all eastward. Apparently there were no contemporaneous marine waters to the west, for only barren red beds (Supai) follow the Pennsylvanian there. These Rico sediments pass in turn into red sandstones, arkoses, and conglomerates suggestive of rapid accumulation (Cutler). Simultaneously, in the nearby area to the west, light-colored sands were accumulating (Coconino)—largely in water but perhaps in part as wind-blown sands. Still farther west, in Cutler time, chiefly limestones (Kaibab) were being formed, suggesting that the open marine waters of the time were to the west. All these sediments were uplifted and eroded and in the Moab region there was local folding. Harrison and Prommel and Crum[1] believe that at this time the most important movement of the salt occurred within the folded areas.

On the surface produced by post-Cutler erosion Lower Triassic sediments were laid down, beginning with fine-grained red beds and in the area to the west passing into more or less non-red marine sediments and again into red sediments (Moenkopi). The Moab region was barely touched by the area in which the non-red marine rocks were laid down, and the general information in hand shows that the open waters of the sea lay toward the west and northwest. There may have been further movement on some of the local areas previously folded, and the beds were then eroded.

On the post-Moenkopi surface were then laid down Upper Triassic fluviatile sediments, beginning generally with a quartz conglomerate or conglomeratic sandstone (Shinarump) and passing into chiefly red and green sandy sediments (Chinle). There may have been again gentle movements on the folded areas and these fluviatile beds were then eroded, at least locally.

Upon the Chinle was deposited in the Moab region a great series of sandy beds (Glen Canyon group and San Rafael group) that seem to show a threefold recurrence of conditions which permitted accumulation of considerable thicknesses of clean sand, in part aeolian in origin, in part waterlaid. Conditions were only similar, however, and not identical, for each of the resultant sandstones has its own characteristics. Following each of the great sandstones thin-bedded red sandstones were deposited, again only similar and not identical. There may have been one widespread in-

[1] T. S. Harrison, *op. cit.*; H. W. C. Prommel and H. E. Crum, *op. cit.*

terruption in the sequence of sediments, but there were certainly many minor local interruptions. Some of the features of the sediments are extremely difficult to interpret in terms of conditions of sedimentation, for example, the crinkling of the Carmel formation between uncrinkled beds above and below. Off to the west and north, during the later part of this period of accumulation of thick sands in the Moab region, were fluctuating bodies of marine water, though there is little organic evidence that they penetrated into the Moab region.

The Jurassic beds were probably eroded and upon them were laid fluviatile sediments, assigned with doubt to the Cretaceous, containing abundant remains of dinosaurs (Morrison), the materials chiefly non-red sandstone, mudstone, and conglomerate. These were eroded and upon them were laid the familiar Dakota (?) sandstone, which in its turn passed upward into marine mudstones and shales (Mancos). Very much later all these beds were disturbed by renewed movements on the folds, by large scale faulting, and by igneous intrusions. The latest features of the region are general uplift and deep trenching by the streams, which Harrison connects intimately with the movement of salt and gypsum under some of the domes in the region.

STRUCTURAL HISTORY OF PARTS OF SOUTHEASTERN UTAH FROM INTERPRETATION OF GEOLOGIC SECTIONS[1]

H. W. C. PROMMEL[2] AND H. E. CRUM[3]
Denver, Colorado, and Amarillo, Texas

ABSTRACT

This paper briefly summarizes recent developments on some of the anticlines of southeastern Utah. Results of detailed studies of the stratigraphy and structure of the Green River Desert during the summer of 1926 are set forth. These studies revealed the presence of a broad intermontane area which was uplifted repeatedly during Mesozoic time, while the surrounding areas apparently remained undisturbed until Cenozoic time. The respective periods at which disturbances occurred in the various parts of this region are considered by the writers of prime importance in the problem of oil accumulation.

This paper contains replies to criticisms received by the writers on their paper entitled "Salt Domes of Permian and Pennsylvanian Age in Southeastern Utah and Their Influence on Oil Accumulation,"[4] which was read before the Western States Convention at Denver, Colorado, in September, 1926.

INTRODUCTION

During the past twenty years, persistent but spasmodic efforts have been put forth to find oil in commercial quantities in southeastern Utah. These efforts have been in the nature of isolated test wells drilled on local domes or anticlines with little or no attempt to solve the historical and stratigraphic questions involved in the problem of oil-finding. Many of these early tests are now known to have reached insufficient depths; while others were located on unpromising anticlines from the standpoint of gathering-areas, probable waters in the sands, and the ages at which the anticlines were formed.

In December, 1925, the pioneer well on the Cane Creek anticline, near Moab, Utah, blew in and produced a large quantity of high-grade oil before being brought under control. This well attracted wide attention, due to its location at the bottom of the canyon of Colorado River and to

[1] Read by title before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, May 11, 1927.

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[3] Consulting geologist, 1205 Polk Street, Amarillo, Texas.

[4] *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 4 (1927), pp. 373–93.

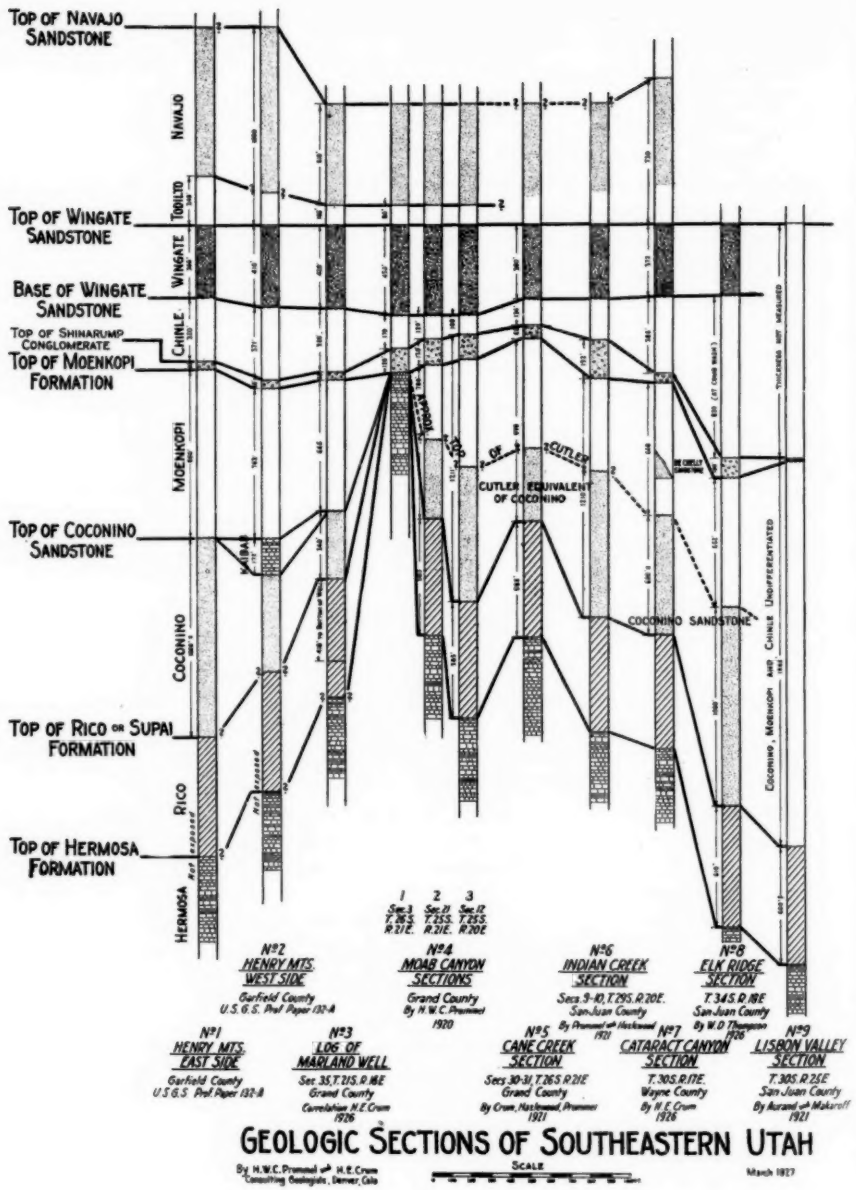
TOP OF NAVAJO SANDSTONE
NAVAJO
TOP OF WINGATE SANDSTONE
WINGATE
BASE OF WINGATE SANDSTONE
CHINLE
TOP OF SHINARUMP CONGLOMERATE
TOP OF MOENKOPI FORMATION
MOENKOPI
TOP OF COCONINO SANDSTONE
COCONINO
TOP OF RICO OR SUPAI FORMATION
RICO
TOP OF HERMOSA FORMATION
HERMOSA
CUTLER EQUIVALENT OF COCONINO
COCONINO SANDSTONE
COCONINO, MOENKOPI AND CHINLE UNDIFFERENTIATED
No 1 HENRY MTS. EAST SIDE
Garfield County U.S.G.S. Prof. Paper 132-A
No 2 HENRY MTS. WEST SIDE
Garfield County U.S.G.S. Prof. Paper 132-A
No 3 LOG OF MARLAND WELL
Sec. 35, T. 31S. R. 18E Grand County
Correlation H.E. Crum 1926
No 4 MOAB CANYON SECTIONS
Grand County By H.W.C. Prommel 1920
No 5 CANE CREEK SECTION
Secs 30-31, T. 26S. R. 21E Grand County
By Crum, Hasbrouck, Prommel 1921
No 6 INDIAN CREEK SECTION
Secs. 9-10, T. 29S. R. 20E. San Juan County
By Prommel and Hasbrouck 1921
No 7 CATARACT CANYON SECTION
T. 30S. R. 17E. Wayne County
By H.E. Crum 1926
No 8 ELK RIDGE SECTION
T. 34S. R. 18E San Juan County
By W.D. Thompson 1926
No 9 LISBON VALLEY SECTION
T. 30S. R. 25E San Juan County
By Herard and Makroff 1921
GEOLOGIC SECTIONS OF SOUTHEASTERN UTAH
By H.W.C. Prommel and H.E. Crum Consulting Geologists, Denver, Colo
SCALE
March 1927

FIG. 1

the fact that the oil was coming from a salt formation in the lower Pennsylvanian (?) series. Due to inability to secure a successful water shut-off at 2,028 feet, the well was drilled deeper through an almost continuous salt series; and at two other horizons, namely, 3,627 and 4,970 feet, flows of oil and gas in large quantities were found. Inability to solve the casing problems, however, has made it impossible for the operators to determine the real worth of all three showings. A somewhat similar history has attended the drilling of the adjoining Shafer anticline. Although no commercial well has yet been saved, the findings have demonstrated rather conclusively that oil and gas under great pressure and probably in large commercial quantities are to be obtained in the lower Pennsylvanian (?) and older series of this district. Recently, petroleum gas has been encountered in the upper Hermosa on Gibson dome and Cedar Mesa.

Having carried on the first mapping of the Moab district under the direction of Fisher and Lowrie, of Denver, Colorado, in 1920 and 1921, the writers have followed developments closely, and during 1926 undertook extensive studies of the area lying south and west of the Moab district, in what is known as the "Green River Desert."

Figure 1 of the writers' former paper[1] shows the anticlines of southeastern Utah which are directly involved in the historical discussion. The area to which this paper is confined is the intermontane region lying between the Henry, La Sal, and Abajo mountains, Elk Ridge, and the San Rafael Swell, all of which are uplifts of prominence. The intermontane area is a relatively low region in which minor folds or anticlines are developed.

The mountain-building movement which produced the almost complete circle of uplifts about the low-lying intermontane region took place following the Cretaceous period. It is the purpose of this paper to show by a study of geologic sections that prior to this post-Cretaceous mountain-building activity, the present intermontane area had been the scene of repeated uplift during Mesozoic times, while the present areas of uplift were scenes of inactivity during this period.

Figure 1 of this paper shows nine graphic measured sections for comparison. Table I shows the geologic column with notes on deposition and structure. Examination of the formations in ascending order reveals several important features. Wherever the Rico or Supai formation has been measured, it retains a remarkably uniform thickness of approxi-

[1] H. W. C. Prommel and H. E. Crum, "Salt Domes of Permian and Pennsylvanian Age and Their Influence on Oil Accumulation," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 4 (1927), pp. 373–93.

TABLE I

Geologic Formations of Southeastern Utah with Notes of Depositional and Structural History

System	Formation	Thickness and Character	Remarks
Tertiary	Wasatch	2,000 feet of varicolored shales, and sandstones	Physiographic evidence shows that present pattern of Colorado River drainage was established on Tertiary plain
	Period of greatest deformation and mountain-building. Formation of La Sal, Abajo, and Henry mountains; also Elk Ridge and San Rafael anticlines and the system of major faults		
Cretaceous	Equivalents of Laramie, Lewis, Mesaverde, and Mancos	3,500 feet of bluish and gray shales and yellowish sands with lignite	Deposition of marine sandstone and shales
	Dakota sandstone	0–100 feet of conglomeratic sandstone	Deposition by shifting streams (?) over eroded surface of Morrison formation
	— Unconformity —		
Cretaceous (?)	McElmo Morrison	Bluish-gray sandy banded shales and sandstones with local gypsum beds	In part, deposition of shifting streams. In part, marine shales
	Angular and erosional unconformity. Sharply defined east of San Rafael Swell on the Sweetwater area of the Nequoia Arch		
Jurassic.....	Entrada formation	200–1,430 feet of red and tan sands and red shales	Deposition of cross-bedded sandstones and red shales. Formation thickest west of Henry Mountains and thinnest on Nequoia Arch
	Carmel formation	75–450 feet of red and blue sandy shale with local gypsum	Marine deposition. Thinnest on Nequoia Arch, thickening toward San Rafael Swell
	— Unconformity —		
	Navajo sandstone	Buff, gray, and white cross-bedded sandstone with limestone	Aeolian deposit, 1,000+ feet thick around Henry Mountains; 500 feet thick on Nequoia Arch
	Todilto formation	75–250 feet of interbedded sands and shales	Water deposit. Lower part in places included in Vermillion Cliff. Thin-bedded
	Wingate sandstone	300–500 feet of reddish-brown massive sandstone	Aeolian deposit of almost constant thickness. Some thin limestone lenses. Prominent cliff-maker
	Angular and erosional unconformity. Uplift probably greatest in the Moab district		
Triassic	Chinle formation	120–1,000 feet of variegated marls and sands and fossil wood	Continental deposit. Thickest in Henry Mountains and Elk Ridge and thinnest in Moab district
	Shinarump conglomerate	0–250 feet of conglomeratic sandstone with fossil wood	Deposit by shifting streams. Variation in thickness due to deposition on eroded surface of Moenkopi
	Widespread unconformity as result of uplift and erosion of Moenkopi beds. Truncation sharpest on local folds such as Cane Creek		
	Moenkopi formation	310–1,100 feet of red and brown shale and sandstone	Marine and continental deposit. Rests on eroded surface of Permian beds
	— Unconformity? —		
Permian	Kaibab limestone	0–250 feet of yellow dolomitic limestone	Marine deposit. Thins out eastward. Absent east of Henry Mountains
	Coconino	0–1,000 feet of tan to gray sandstone	Aeolian deposit. Overlain by Triassic beds east of Henry Mountains. Thickest near Elk Ridge, thinnest in Moab district
	Unconformity local? Rico or Supai	200–600 feet of red sandstone, red shale, and purplish limes	Limestone marine. Shafer limestone at top. Rather uniform thickness
Pennsylvanian	Hermosa limestone	1,600 feet gray limestone with sandstones in upper part	Upper part exposed on Colorado River below Moab. Showings of oil in San Juan region and Gibson dome
(?)	Dark shale, gypsum, anhydrite, salt	Dark shale, intruded by salt, anhydrite, and gypsum with thin beds of shale 3,000 feet	Saline facies of lower Pennsylvanian (?) or older formationa. Oil and gas at Cane Creek and Shafer domes

mately 600 feet and rests conformably on the underlying Hermosa limestone series of Pennsylvanian age. The Hermosa, likewise, where it has been penetrated by the drill, shows a constant thickness of approximately 1,600 feet. It is therefore inferred that no disturbance occurred during the deposition of the Hermosa or Rico formations.

Table II shows the comparative thicknesses of measured sections above the Rico. Resting on the top of the Rico is the Coconino sand-

TABLE II

COMPARATIVE THICKNESSES (IN FEET) OF MEASURED GEOLOGIC SECTIONS OF SOUTHEASTERN UTAH

FORMATION	AREA OF LITTLE DISTURBANCE			AREA OF REPEATED UPLIFT DURING MESOZOIC						AREA OF LITTLE DISTURBANCE
	Northwest of Henry Mts.	Southwest of Henry Mts.	East of Henry Mts.	Green River	Nequoia Arch	Moab Canyon	Cane Creek	Indian Creek	Cataract Canyon	Elk Ridge
McElmo or Morrison	.....	560	.....	.....	4,004	.....	.....	.....	.....	.....
Entrada	.....	1,400	300	.....	250	.....	.....	.....	.....	.....
Carmel	.....	450	.....	.....	100	.....	.....	.....	.....	.....
Navajo	.....	1,400	.....	510	550	453	.....	.....	.....	.....
Todilto	.....	160	.....	105	249	80	.....	.....	220	.....
Wingate	410	340	366	420	360	450	380	375	372	.....
Chinle	371	500	320	310	.....	120	136	200	385	820
Shinarump	0–40	40–110	20–60	40	.....	130	65	192	42	100
Moenkopi	763	480	850	680	.....	0,779, 1,211 Mean 663	975	1,055	668	652
Kaibab	172	175	.....	.....	.....	.....	.....	.....	.....	.....
Coconino	1,000±	1,000±	1,000±	340	.....	.....	.....	155	600	1,000
Total thickness from base of Wingate to base of Coconino	2,346	2,195	2,190	1,370	.....	913	1,176	1,602	1,695	2,572

stone, also of Permian age. A slight unconformity was observed between these two formations along Cataract Canyon where the Shafer limestone, which normally lies at the top of the Rico, was missing locally. This may mean a slight disturbance prior to Coconino deposition.

The Coconino sandstone reaches its maximum thickness of 1,000 feet in the vicinity of Elk Ridge and also along Colorado River east of the Henry Mountains. A lesser thickness was measured along Cataract Canyon where it ranges from 600 to 700 feet, and a still lesser thickness at Indian Creek. On Shafer and Cane Creek anticlines the lower sandy portions of the Moenkopi may be the equivalent of the Coconino, although there is a decided change in lithologic character. The U. S.

Geological Survey[1] is leaning toward a classification which would place the Lower Moenkopi section of Moab Canyon and the Colorado River structures, within the Cutler formation, and show a southward transition zone from Cutler into Coconino. The upper surface of the Coconino shows erosion in this region, which fact, together with its thinning toward the Moab district and the Green River Desert, may mean that uplift and subsequent erosion took place in the latter districts, during which the upper portion of the Coconino sandstone was removed. The Kaibab limestone is still present west of the Henry Mountains but, either on account of non-deposition or removal by erosion prior to Moenkopi deposition, becomes thinner to the eastward and is absent east of the Henry Mountains.

Resting on the eroded surface of the Kaibab limestone west of the Henry Mountains, and on the Coconino sandstone east of the Henry Mountains, is the Triassic Moenkopi formation. It consists mainly of red sandstones and red shales with a prominent lentil of sandstone in the lower portion. The Moenkopi has a wide range in thickness, due to the notable unconformity at the top, as well as several observed minor unconformities within this formation. The eroded upper surface is overlain by the Shinarump conglomerate. With the exception of the Moab Canyon section, where, according to observations of the U. S. Geological Survey, a conglomerate member of the Chinle has been mistaken for it,[2] the Shinarump conglomerate is easily recognizable over the entire area. This unconformity at the top of the Moenkopi is probably the most prominent one in this region and is evidence not only of widespread uplift but of local folding at this period. That local folding occurred at this time is plainly shown by the rapidity with which the Moenkopi beds dip outward from the crest of Cane Creek anticline. The overlying beds incline in the same direction but at a lesser degree of dip. From this evidence it would appear that the forces which acted at the close of the Moenkopi to produce folding at Cane Creek anticline were similar to the forces which later accentuated this fold. The writers are of the opinion that forces acting in a vertical direction from below contributed to the folding. This constitutes important argument in support of their theory of salt flowage in the formations of the Colorado River anticlines.

The Shinarump conglomerate was laid down on the eroded surface of the Moenkopi formation. It consists of coarse sandstone, with interbedded lenses of conglomerate containing pebbles of chert, quartzite, and

[1] Verbal communication, C. E. Dobbin and J. B. Reeside, Jr.

[2] *Ibid.*

silicified wood. It is remarkably persistent over a broad area. The variations in thickness are due to the filling of depressions in the surface of the Moenkopi.

Resting on the Shinarump with apparent conformity is the Chinle formation, at the top of which again appears an erosional and angular unconformity. From the comparative sections in Figure 1 and in Table II it is apparent that the Moab district and the Nequoia Arch were again the scene of uplift, as shown by the thinness of this formation in these localities compared with the surrounding territory.

During the deposition of the Wingate sandstone constant conditions prevailed, as evidenced by its remarkably uniform thickness and character, which make it the most prominent and unmistakable formation of the entire region. Upon it rests the Todilto formation, which, although much more variable in character, retains a rather uniform thickness. No widespread unconformities are in evidence throughout the deposition of these last-named formations, but the U.S. Geological Survey[1] reports local unconformities at the top of the Wingate sandstone.

The succeeding Navajo sandstone ranges in thickness from 1,000 feet in the vicinity of the Henry Mountains to 550 feet in the Nequoia Arch. This may mean evidence of further uplift in the Moab district and the Nequoia Arch. The overlying Carmel shale is also thinner over the Nequoia Arch than in the Henry Mountain district.

The Entrada formation, which overlies the Carmel shale, is known to be the thinnest on the Nequoia Arch. At the top of the Entrada is a decided unconformity, which is noticeable in the Sweetwater area of the Nequoia Arch, where the local folding in the Entrada formation is not reflected in the overlying McElmo or Morrison formation.

The significance of the foregoing discussion of comparative geologic sections lies in the fact that wherever any one formation has been studied and measured over the entire region a consistent thinning of this formation is observed in the direction of the Nequoia Arch and the Moab district. With the possible exception of the Coconino sandstone, this thinning is not accompanied by lithologic change but is rather due in each case to uplift followed by partial or total erosion of the formation. The pre-Triassic erosion removed a large portion of the Coconino, as shown by Figure 1 and Table II; while erosion succeeding the Moenkopi and the Chinle formations likewise removed a considerable portion of these formations.

[1] Longwell, Miser, Bryan, Moore, and Page, "Rock Formations in the Colorado Plateau of Southeastern Utah and Northern Arizona," *U. S. Geol. Survey Prof. Paper 132-A*.

Although the intermontane area was being repeatedly uplifted and eroded during the Mesozoic, a further study of the geologic sections shows that the surrounding areas remained comparatively inactive during this period. Quantitatively, the amount of uplift of the intermontane area compared to the surrounding district, measured from the base of the Wingate sandstone to the top of the Rico formation as computed from the sections, is 1,400 ± feet. This amount of uplift is sufficient, in the opinion of the writers, to be highly important in the quest for petroleum in this district. It seems plausible to suppose that petroleum existing in the underlying Hermosa formation would have migrated into the area of uplift as outlined above and thence into the local anticlines of the uplifted area. If such migration occurred, the intermontane area is more attractive to the oil prospector than the surrounding area, which has been demonstrated to have occupied a comparatively low structural position throughout the Permian, Triassic, Jurassic, and Cretaceous periods and to have reached its present highly elevated structural position only since Cenozoic time. The finding of oil on Cane Creek and of gas on Cane Creek and Shafer domes would seem to indicate that such accumulation did occur. Drilling on Elk Ridge has not proceeded far enough as yet to justify a decision as to whether or not Pennsylvanian oil will be found in this post-Cretaceous anticline. Due to secondary migration, oil may also be found on anticlines of post-Cretaceous age in southeastern Utah.

Of great scientific interest is the occurrence of a great thickness of salt in the Cane Creek and Shafer anticlines on Colorado River, the salt ranging in depth from 1,865 to 5,270 feet (March, 1927) with only thin layers or inclusions (?) of shale and anhydrite. More than 80 per cent of the material penetrated below 2,000 feet has been rock salt. In March, 1926, Harrison[1] set forth his theory of salt flowage due to differential loading along Colorado River to account for the anticlines found along this river. At that time the writers were forming the same opinion of salt flowage as being responsible for the Colorado River anticlines, but did not concur with Harrison as to the reason for such flowage. A study of the unconformities along the flanks of Cane Creek anticline show positively that this fold came into existence as far back as the close of the Moenkopi, and possibly during pre-Triassic movement, at which times the condition of differential loading as now seen along the Colorado River Canyon did not exist. Furthermore, it has been shown by comparative

[1] T. S. Harrison, "Colorado-Utah Salt Domes" (paper read before the Dallas meeting of the American Association of Petroleum Geologists, March, 1926), this *Bull.*, Vol. 11 (1927), pp. 111–33.

geologic sections that forces have been at work at various times since the close of the Permian elevating this district.

A summary of the evidence which leads the writers to believe that salt flowage during several comparatively early geologic periods is primarily responsible for the formation of local anticlines of the intermontane region is as follows:

1. Presence of massive, non-bedded gypsum, at the surface, along the axis of anticlines such as Salt Valley and Moab and in contact with Jurassic strata, which strata do not contain salt or anhydrite in the flanks of such anticlines.

2. The Pennsylvanian Hermosa formation, of unquestionable marine origin, is exposed at intervals along Colorado River from Moab southward to the junction of Colorado and Fremont rivers. Not more than half of this marine formation, which consists of 1,600 feet of massive limestones with some thin gray sandstones, has been exposed above the bed of Colorado River by erosion throughout this distance. Arched gypsum masses are present in Cataract Canyon, near the middle of this marine formation. Anhydrite and gypsum indicate arid conditions during their time of deposition. The presence of a large mass of non-bedded, arched gypsum near the middle of a distinctively marine series is suggestive of salt-dome cap-rock conditions rather than change of anhydrite of a bedded deposit into gypsum. Such change in the cap-rock of a possible salt dome, may, however, have accentuated reflections of some of the primary salt domes and salt anticlines of southeastern Utah. Such phenomena may fully account for Harrison's Meander anticline along Colorado River.

3. Presence of plentiful gypsum cap-rock where the salt has been intruded high into the sedimentary series (Moab, Salt Valley); presence of a smaller amount of cap-rock where the salt has not been intruded as high into the sedimentary series (Spanish Bottom dome); entire absence of cap-rock where the salt is deep-seated and has not come in contact with percolating ground waters (Cane Creek and Shafer anticlines).

4. Unconformities on local folds showing growth of the anticlines by repeated uplift, together with the finding of great thicknesses of deep-seated salt in the drilling of these folds.

5. Presence of Mississippian fossils in isolated outcrop along the faulted crest of Salt Valley anticline, where the gypsum outcrop is in contact with Jurassic strata.

6. Similarity in areal extent and character, as well as reflections of different periods of folding expressed in the shape of anticlines of the Nequoia Arch and the Colorado River anticlines below Moab. Vertical

thrust of the salt due to its squeezing by lateral stresses appears to have been the primary movement forming the anticlines. Subsequent warping of the domal shape of the folds took place during post-Cretaceous activity, at which time faulting and fracturing also occurred.

From the foregoing it is apparent that the writers do not believe that masses of salt, gypsum, and anhydrite appearing on the surface and encountered in test wells on anticlines of southeastern Utah are regularly bedded in the strata. If they are regularly bedded, as some geologists maintain, then one should expect to find bedded salt and anhydrite in almost every formation of the geologic column of southeastern Utah. As a matter of fact, a study of the geologic column away from the disturbed areas reveals the fact that these minerals are extremely rare in this district. If hydration has occurred, as is conceivable, it is our opinion that the alteration has taken place in the anhydrite cap-rock of a probable buried salt mass rather than of bedded anhydrite.

It is unfortunate that the drilling of the wells on the Colorado River anticlines was carried on with cable tools after the salt was reached. Although these wells have penetrated more than 3,000 feet of salt, to the writer's knowledge no salt cores have been obtained. Microscopic studies have been made of drill cuttings from these wells, but no results or findings have been published by the drilling companies.

In conclusion, the writers summarize the results of these studies as follows:

Six distinct periods of disturbance and erosion, ranging in age from Permian to late Cretaceous or Tertiary, can be identified in southeastern Utah. Five of these movements took place prior to post-Cretaceous times. Unconformities indicate not only that there was regional uplift in parts of southeastern Utah but that individual folds were given their own impulses at such times. Salt and anhydrite, originally present as a saline facies in the lower Pennsylvanian (?) or lower series, were subjected to folding and flowage during the various movements. That the La Sal, Henry, and Abajo mountains had something to do with the present shape of anticlines is recognized, so that primary salt ridges and salt anticlines as well as secondary salt domes may be present in southeastern Utah. Post-Cretaceous igneous activity is pronounced near Elk Ridge, and the dome-like gypsum mass of Spanish Bottom may represent the cap-rock of a salt dome which was squeezed into the overlying formations from a primary salt ridge or salt anticline. The latter, we believe, had its inception prior to post-Cretaceous folding, as evidenced by a study of geological sections of the region. That older anticlines were affected to

some extent by post-Cretaceous folding is evidenced by many fracture planes and minor faults which traverse deeper-seated salt domes and salt anticlines, as well as by intense faulting along salt ridges or salt anticlines and domes which were intruded by flowage high into the stratigraphic column.

SUBSEQUENT NOTE

Since this paper was written, the Empire Gas and Fuel Company well, drilling on the Gibson dome in San Juan County, Utah, passed out of massive limestone at a depth of 1,922 feet. The well started 62 feet above the Shafer limestone; and if penetrating a true section, it should not reach the base of the Hermosa limestone until a depth of 2,262 feet has been reached. Below 1,922 feet the well encountered black shale to a depth of 2,005 feet. Below this, to a depth of 3,400 feet, salt, with some thin layers of shale and thin limestones, has been drilled through. This shows that Gibson dome is a reflection of a salt dome and that intrusion of salt has taken place into the lower 200 feet of Hermosa limestone on this anticline.

FIG. 2.—Cores of salt from well in southwestern Colorado, showing salt flowage lines.

CORES OF SALT FROM WELL IN SOUTHWESTERN COLORADO SHOWING SALT FLOWAGE LINES

Salt cores (Fig. 2) from the Wilcox well No. 2 of the General Petroleum Company in the N.½ SE.¼, Sec. 6, T. 47 N. R. 19 W., Montrose County, Colo-

rado, show distinct salt flowage lines. The salt appears to be thin bedded, each bed being separated from the other by thin shale partings. These shale partings clearly reveal the structural attitudes of the salt from this salt dome.

Core No. 1, at the left of the photograph, shows the thin shale partings, as well as a break in the mixture of salt and anhydrite which appears to have later been filled by pure salt. This core was taken at a depth of 3,734 feet in the well.

Core No. 2 was taken at a depth of 4,020 feet in the well. It plainly shows distorted bedding planes.

Core No. 3, third core from the left in the photograph, shows similar conditions to core No. 1. This core was taken at a depth of 3,740 feet in the well. This core shows a round top, indicating some dissolution of the salt while coring.

Core No. 4 was taken at a depth of 3,984 feet. It is part of a core which split along the nearly vertical bedding planes.

The Wilcox No. 2 well is located about three fourths of a mile from the crest of the Paradox Valley anticline. The cores taken from the well show that the salt has been subjected to considerable flowage. Conditions as shown by these cores uphold contentions made by the writers in the foregoing paper, and point to the importance of drilling flank wells on these anticlines of southeastern Utah and southwestern Colorado before the accumulation in them of oil and gas in commercial quantities can be considered as proved or disproved.

The Wilcox No. 2 well starts in anhydrite at the surface.

A PETROGRAPHIC STUDY OF THE PRE-CAMBRIAN OF KANSAS[1]

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ABSTRACT

Many wells have penetrated the pre-Cambrian surface along the "granite ridge" and elsewhere in Kansas. Microscopic examination of cuttings from wells which have gone some distance into the ancient crystallines confirms the idea that the Kansas pre-Cambrian rocks compose a metamorphic complex, mainly gneiss and schist, rather than granite. Some wells have gone directly from the sedimentary rocks into schist, but the pre-Cambrian rocks have not been recognized as such until a much deeper granite (probably gneiss) was struck.

Failure to recognize the pre-Cambrian where it appears in some other form than granite has led to much futile drilling in Kansas. It is the writer's intention to describe and emphasize the importance of the more common crystalline rock types that have been encountered by deep wells within the state.

The presence beneath the surface of Kansas of a well-defined and prominent pre-Cambrian ridge is well known. This ridge extends from Nemaha County on the north to eastern Sumner County on the southern border of the state. The summit of the ridge lies within 500 feet of the surface in northern Kansas and over 3,000 feet in depth in southern Kansas. Many wells drilled on and near the axis of this ridge have penetrated the pre-Cambrian surface. Also east of the ridge, to and beyond the Missouri state line, several deep wells have drilled into the ancient crystallines. A few wells have likewise penetrated the pre-Cambrian surface west of the granite ridge. One well, in particular, located in the Cheyenne Bottoms of Barton County, went almost 300 feet into the pre-Cambrian. Wells in Nebraska, Missouri, and Oklahoma have reached the pre-Cambrian and in addition the ancient crystallines outcrop at the surface in the two last-named states.[3]

[1] Read before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, May 5, 1927.

[2] Acting state geologist. Introduced by John L. Rich.

[3] Charles N. Gould, "Crystalline Rocks of the Plains," *Bull. Geol. Soc. Amer.*, Vol. 39 (Sept. 30, 1923), pp. 541–60.

A variety of rocks has been found to compose the pre-Cambrian floor. Brief descriptions of the more important types follow.

GRANITE OR GNEISS

With the ordinary small fragments of rocks secured by the cable-tool method of drilling it is difficult or impossible to distinguish granite from gneiss. The mineralogical composition may be the same for either type of rock. During the remainder of this report the holocrystalline acidic pre-Cambrian rock will be referred to as granite, which is the common usage, although there is considerable evidence that much of this granite is in reality gneiss. All the pre-Cambrian wells drilled along the ridge have encountered this type of rock. Most, but not all, of the wells drilled to the east and west of the granite ridge, which have penetrated the pre-Cambrian surface, have likewise drilled into some granite. It is reported that the core drill of the Raytown, Missouri, well showed the hole bottomed in a granite which was possibly gneissoid.[1] Raytown lies a few miles southeast of Kansas City.

SCHIST

Schist is second in quantitative importance to the granite or gneiss. Several wells on and near the axis of the ridge have gone either directly from Paleozoic rocks into schist or have found zones of schist lying beneath rock which had been logged as granite. A few examples will suffice: (1) *Marshall County*. The Beattie well was reported to have drilled into crystalline rocks for nearly 2,000 feet. Within this 2,000 feet was found a hornblende chlorite schist lying below a hornblendite.[2] (2) *Riley County*. The Zeandale well encountered schist.[3] (3) *Marion County*. The Milne No. 1 well, in the southeastern part of the county, drilled the lowermost 260 feet in a hornblende schist.[4] (4) *Chase County*. The writer has observed schist pebbles in granite-wash cuttings from the Lips No. 1 well in northwestern Chase County.

Probably the best example of a schist well in Kansas is the Breitkreutz well in northern Greenwood County. However, the schist was originally logged as shale and consequently the pre-Cambrian surface was mapped 650 feet lower than it really is, creating an abnormal, closed depression.

[1] Henry Hinds and F. C. Greene, "Leavenworth-Smithville Folio, Kans.-Mo.," *U. S. Geol. Survey Folio 206* (1917), p. 4.

[2] R. C. Moore, unpublished list.

[3] Erasmus Haworth, "Crystalline Rocks in Kansas," *State Geol. Survey of Kansas Bull. 2* (1915), p. 23.

[4] R. C. Moore, unpublished list.

At a depth of 3,500 feet the Breitkreutz well cuttings change from a limy sand to a conglomerate consisting almost entirely of schist pebbles. The pebbles differed in size considerably and were cemented by limonite. The conglomerate is exceptionally thick, for it continues without essential change in character down to a depth of 4,150 feet. Here the bed-rock schist commences and it is at this point that the surface of the pre-Cambrian should be mapped. The schist is highly micaceous. At a depth of 4,774 feet it gives way to white quartzite which continues 26 feet farther to the bottom of the hole.

The Copper-Everleigh well in Barton County, south of the Russell County field, at about 4,150 feet went from an arkose into solid pre-Cambrian. From this depth down to the bottom of the hole, a little less than 300 feet lower, the rocks alternated between gneiss and schist. The suite of cuttings of this well which was examined by the writer was not entirely complete, but in it at least a half-dozen such alternations were encountered.

J. E. Todd in 1895 reported the presence of schist in a well drilled in Pawnee City, Nebraska.[1] This town is located a few miles north of northwestern Nemaha County.

A peculiar circumstance is that several of the schist wells have reported consistent oil shows and the operators consequently have been encouraged to drill for considerable distances into this material.

OTHER ROCKS

In addition to granite, gneiss, and schist, several other types of rocks have been reported as occurring within the pre-Cambrian. None of these has been observed personally by the writer.

1. *Basic igneous.*—The Beattie well of Marshall County, which has already been referred to, reported the presence of hornblendite. The Elmdale No. 2 in Chase County went through 60 feet of diabase or diorite below the granite surface.[2]

2. *Quartz porphyry.*—This rock has been described occurring with granite in the Kaufman well near Elmdale, Chase County.[3]

3. *Crystalline limestone.*—R. S. Knappen[4] has reported that cuttings from the Seneca well in Nemaha County and the Frankfort well in Mar-

[1] *Amer. Geologist*, Vol. 15 (Jan., 1895), p. 64.

[2] Charles H. Taylor, "The Granites of Kansas," *Bull. Southwestern Assoc. Petrol. Geol.*, Vol. 1 (1917), pp. 111–26.

[3] R. C. Moore and Winthrop P. Haynes, "Oil and Gas Resources of Kansas," *State Geol. Survey of Kansas Bull. 3* (1917), p. 163.

[4] Discussion following paper by Charles N. Gould, "Crystalline Rocks of the Plains," *Bull. Geol. Soc. Amer.*, Vol. 34 (Sept. 30, 1923), p. 558.

shall County showed the presence in that region of crystalline limestone within the pre-Cambrian.

In examining the wash of the re-worked pre-Cambrian material in the Barton County well the writer came across a zone of well-rounded calcite grains. Because the surrounding material was obviously derived from the pre-Cambrian terrain it may be assumed that the rounded calcite grains likewise came from the ancient rocks.

4. *Quartzite.*—R. C. Moore[1] reports that the last 30 feet of the Breitkreutz well was drilled in an unmistakable quartzite.

Failure to identify the schists as pre-Cambrian has led to much useless drilling within the state of Kansas. When fragments of any size are produced identification is simple. But when cut into small bits the polarizing microscope is an absolute necessity in distinguishing metamorphic from sedimentary rocks. The schists examined by the writer were characterized by large amounts of feldspar (generally microcline) and biotite. As both of these minerals are relatively unstable they would not be expected to occur in abundance in sediments, except in a wash from a nearby crystalline bed-rock source. Minerals typical of metamorphism, such as andalusite and sillimanite, are often present. A criterion to distinguish sedimentary from igneous and metamorphic rocks that is often quoted is the greater degree of angularity of the mineral grains in the latter types. However, this is most difficult of application. Closely and tightly cemented grains of a sedimentary rock may be considerably fractured during drilling and thus appear very angular. On the other hand, the mineral grains in the pre-Cambrian rocks may be surprisingly spherical, especially if the rock is composed of metamorphosed sediments.

The relative difference in hardness is the best way to distinguish wash from bed rock. To one unacquainted with the drilling history of a well this difference is shown by the presence of an exceptional number of drill-steel fragments in the cuttings from the harder rock. Some cuttings submitted to the writer for examination contained steel ranging in amounts from 50 to 70 per cent.

The conclusion is that the sedimentary rocks of Kansas and adjoining states overlie a pre-Cambrian metamorphic complex. The principal rocks are granite or granite gneiss and schist. In examining cuttings from deep wells in Kansas and adjoining states one should be on the alert for a variety of rocks and not merely for granite.

[1] Verbal communication.

THE GEOLOGY OF THE SAN MARCOS QUADRANGLE, TEXAS[1]

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ABSTRACT

The San Marcos quadrangle is located on the landward edge of the Texas Gulf Coastal Plain, about 60 miles southeast of the Texas Central Mineral Region. The area of the quadrangle is about 1,060 square miles, or nearly $\frac{1}{25}$ of the area of Texas.

The surface formations comprise the upper Comanchean; all of the Upper Cretaceous; and the Midway, Wilcox, and Claiborne of the Eocene Tertiary. All the upper Comanchean and Upper Cretaceous formations exposed at the surface are encountered in the subsurface on the area of Tertiary outcrops. No evidence of major disconformities is revealed by the drill.

The quadrangle embraces a sector of the Balcones fault zone. The regional dip throughout this area is southeasterly. The principal structures are faults roughly paralleling the strike of the formations. Four distinct fault systems occur within this area: the main Balcones, with the downthrown side on the southeast; and the Staples–Lytton Springs, Luling–Burdette Wells–Cibolo, and the Manford (Bethany Church) systems, which have the downthrown side on the northwest.

Two oil fields occur within the area: the Luling and the Lytton Springs fields. The Luling structure is a closed uplift of the faulted monocline type and is located on the lower Wilcox outcrop. The Lytton Springs structure is a domal uplift associated with extrusive and intrusive igneous material along a small fault and is located on the Midway outcrop. In the Luling field the oil is produced from the top of the Edwards limestone. In the Lytton Springs field the oil is produced from a porous mass of serpentine encountered in the lower Taylor formation.

On December 31, 1926, the total production of the Lytton Springs field was 4,643,000 barrels, and the daily production was about 3,000 barrels. On this date, the total production of the Luling field was 31,672,000 barrels, and the daily production was about 18,900 barrels.

INTRODUCTION

The San Marcos quadrangle is of great geological interest because it embraces several well-defined faults located in the Balcones fault zone, and two important oil fields: the Lytton Springs and the Luling fields. In this paper, the writer desires to illustrate the areal, structural, and petroleum geology of the quadrangle as a whole. He is indebted to Wallace E. Pratt, Sidney Powers, and Frederic H. Lahee for helpful encouragement in the preparation of this paper; to L. T. Barrow and C. E. Cook for valuable subsurface data; and to Roy Dobbins and the *Oil and Gas Journal* for oil-production data. Besides, the writer has availed himself

[1] Read before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor April 11, 1927.

of the information from several published treatises, as indicated in the footnotes.

LOCATION

The San Marcos quadrangle (Fig. 1) is located about 60 miles southeast of the Central Mineral Region[1] and occupies the northwestern margin

FIG. 1.—Map showing location of the San Marcos Quadrangle in Texas

of the Gulf Coastal Plain, the northwestern corner of the quadrangle lying upon the Edwards Plateau. San Marcos River traverses the area in general from the northwest corner to the southeast corner. The quadrangle occupies in part the counties of Caldwell, Guadalupe, Hays, Bastrop, and Gonzales.

TOPOGRAPHY AND DRAINAGE

The general topography is one of rolling plains with low relief. In the San Marcos sector of the quadrangle, the Comanchean limestones of the

[1] J. A. Udden, "Review of Geology of Texas," *University of Texas Bulletin 44* (1916).

Edwards Plateau form a southeast-facing dissected scarp rising about 100 feet above the Upper Cretaceous plain area of the Gulf Coastal Plain. From San Marcos southeastward to Luling, the area is of gently rolling terrain sloping seaward, and lacks prominent topographic features. A few miles east and northeast of Luling, however, the red ferruginous sandstones of the basal Claiborne form a prominent northwestward-facing scarp rising about 150 feet above the rolling plain lying between this point and the town of Luling.

The major part of the area is drained by San Marcos River and its tributaries, the direction of the drainage being dominantly southeast. The southwestern and extreme southern part of the area, however, is drained by Guadalupe River and its tributaries, the direction of this drainage being dominantly east-southeast.

SURFACE GEOLOGY

The regional dip of the strata exposed in this quadrangle (Fig. 2) ranges from 1° to 2° SE. on an average, but locally the dip may be 5° or 6° SE. For the computation of formation thicknesses, the rate of dip of about 100 feet per mile to the southeast seems to suffice in the valley of San Marcos River; but the rate of about 150 feet per mile is more accurate in the northeastern part of the quadrangle.

In the area northwest of the town of San Marcos, on the Edwards Plateau, rocks of Comanchean age are exposed; although near the town some of the Comanchean hills are capped with shales of Eagle Ford age, these latter beds belonging to the base of the Upper Cretaceous in this section of the state. Other exposures of the Eagle Ford occur southwest of San Marcos and along the east bank of Blanco River west of the town of Kyle. The Comanchean rocks known to outcrop northwest of San Marcos are the Buda limestone, Del Rio clays, and the Georgetown-Edwards limestones. It is improbable that any Comanchean rocks older than the Edwards are exposed in the quadrangle.

In the area between Kyle and Blanco River, and extending southward toward San Marcos, the Eagle Ford and the Austin chalk of the Upper Cretaceous are well exposed. East of Kyle and southeast of San Marcos the surface beds are of Taylor age. The Taylor formation is overlain by the Navarro, which occurs at the top of the Upper Cretaceous section in this part of the state. The writer has not attempted to differentiate between the Taylor and the Navarro and has therefore not drawn a contact between the two.

About 9 miles southeast of San Marcos, near the town of Staples, the Cretaceous-Eocene contact occurs. The Navarro is overlain by the Mid-

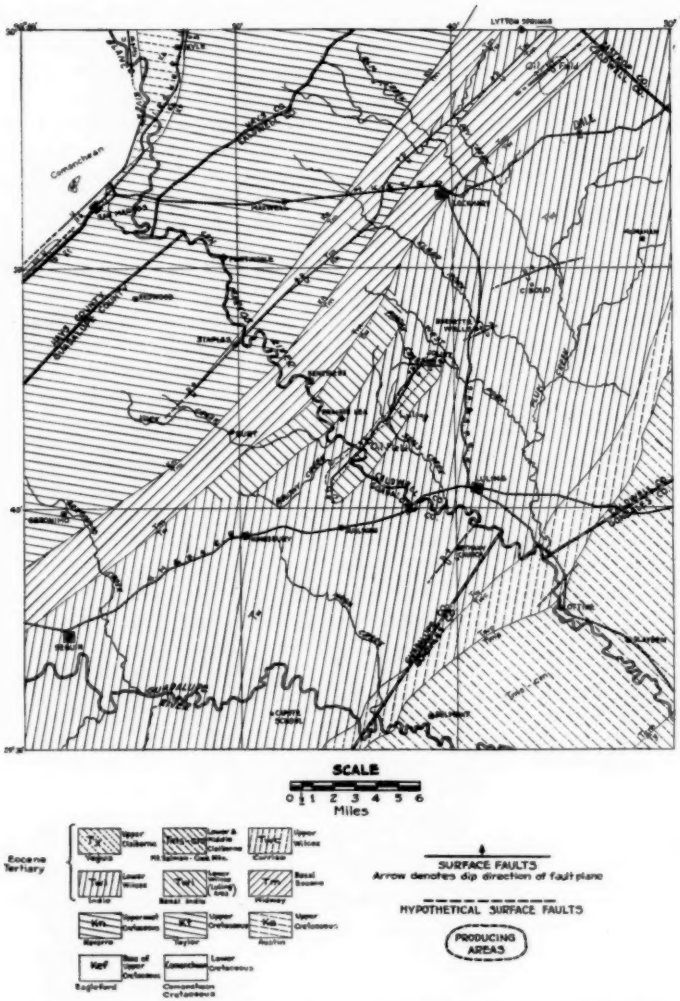

FIG. 2.—Map showing areal geology of the San Marcos Quadrangle of Texas. Base map: reproduction U. S. Geol. Survey Topographical Sheet of San Marcos Quadrangle of Texas.

way of the Eocene Tertiary. The strike of the contact is approximately N. 35° E. Because of major faulting along the Cretaceous-Eocene contact zone, two such contacts occur, this condition being found all along the strike in Caldwell County and a short distance southwestward into Guadalupe County. The Navarro of the Upper Cretaceous and both the Midway and the Wilcox of the Eocene are involved in this repetition due to faulting.

The Indio[1] or lower Wilcox beds overlie the Midway. In the Luling area, the basal argillaceous beds of the Indio can be readily differentiated from the normally overlying sandy beds, but such differentiation cannot satisfactorily be made all along the strike because of lateral variations in lithologic character. Because of faulting in the Luling-field area, the basal Indio beds are uplifted to the surface about 3 miles southeast of the normal-outcrop locality.

In the Bethany Church area south of Luling, and along the strike of the Indio-Carrizo contact, the character of the Upper Indio is remarkably similar to that of the basal beds. The uppermost Indio beds are noticeably argillaceous and fossiliferous and resemble in general aspect the basal beds. At Bethany Church, because of faulting, the uppermost Indio beds are exposed on the downthrown side of a fault of the Luling-fault type.

The Wilcox sediments in this quadrangle and contiguous area are classified by Deussen[2] as belonging to the Indio and Carrizo formations, the Carrizo occurring at the top of the Wilcox. The writer experienced some difficulty in determining the Indio-Carrizo contact, but is convinced that the strike of this contact is approximately northeast, in view of the fact that the dip along this contact zone is southeasterly and in fair agreement with the regional dip and strike throughout the remainder of the quadrangle.

Overlying the uppermost Indio argillaceous beds is a series of loosely consolidated gray sands with local indurations of quartzite. This sand series is referred to the Carrizo and occupies the top of the Wilcox in this section.

The Carrizo–Mount Selman, or rather, the Wilcox-Claiborne contact, is drawn along the contact of the sand series of the Carrizo with a series of moderately indurated red ferruginous sandstones which are referred

[1] A. C. Trowbridge, "A Geologic Reconnaissance in the Gulf Coastal Plain of Texas near the Rio Grande," *U. S. Geol. Survey Prof. Paper 131-D* (1923).

[2] Alexander Deussen, "Geology of the Coastal Plain of Texas West of the Brazos River," *U. S. Geol. Survey Prof. Paper 126* (1924).

to the Mount Selman or basal Claiborne. This red sandstone forms a prominent northwest-facing scarp rising high above the rolling Carrizo-sand plain. This scarp topography is very prominent northward from the town of Ottine but is not of marked prominence southwest of this town.

No attempt is made to differentiate between the Mount Selman and the normally overlying Cook Mountain, but a marked lithologic and paleontologic difference exists between the lower and the upper beds of this group.

The Yegua formation, which normally overlies the Cook Mountain, is the youngest Eocene formation occurring within the quadrangle; and only the lower beds of the Yegua are exposed. In marked contrast to the high sand content of the underlying Cook Mountain, Mount Selman, Carrizo, and Indio formations, the Yegua is predominantly a clay formation. In fact, the general lithologic aspect and the topographic expression of the Yegua are not much unlike those of the basal Eocene Midway.

The Quaternary "upstream-phase" Reynosa chert gravels mantle the interstream uplands and ridges throughout the quadrangle, but the thickness varies greatly and rarely exceeds 20 feet. This formation is best exposed on the upland area surrounding the town of Kingsbury. In other parts of the quadrangle this formation has been re-worked by erosion and generally occurs in the form of residual chert gravels incorporated with the soil mantle. Furthermore, along the southwest side of Plum Creek, both northwest and southeast of Lockhart, the gravels in the "upstream-phase" Reynosa are principally of limestone rather than of chert. This limestone gravel seems to be of Comanchean derivation, thus suggesting the probability that Blanco River formerly flowed southeastward along the present-day valley of Plum Creek.

The exposures of the Upper Cretaceous and Eocene strata, in spite of the occurrence here and there of the "upstream-phase" Reynosa, are common enough throughout the quadrangle to render possible fairly accurate determinations of the surface geology.

SUMMARY DESCRIPTION OF THE SURFACE FORMATIONS

CLAIBORNE EOCENE TERTIARY

Yegua.—300 feet. Dark selenitic clays with ferruginous and calcareous concretions. Rolling typography; heavy black soils; mesquite timber predominating. Lacustrine to marine. Fossils rare.

Cook Mountain.—400 feet. Brown sandy clays, sands, and sandstones, and gray-to-red rust-stained micaceous sandstones. Rolling topography; light-red-

dish sandy clay soils; postoak and blackjack timber predominating. Lacustrine to marine. Fossils fairly common.

Mount Selman.—450 feet. Basal beds consist of moderately indurated, red micaceous sandstone with red and yellow clay inclusions; the induration due to ferruginous cementation. Topography southeast of basal beds is rolling upland with light, sandy, reddish soils; but the basal red sandstones tend to form a dissected northwestward-facing scarp front of rugged topography. Post oak and blackjack timber predominate. Lacustrine. Fossils rare.

WILCOX EOCENE TERTIARY

Carrizo.—250 feet. A white coarse-grained sand, here and there rust-stained, with local areas of quartzitic induration. Rolling topography; very light sandy soils; post oak, blackjack, and hickory timber. Lacustrine. Fossils rare.

Indio.—1,250 feet. Basal beds in Luling area consist of 100 to 200 feet of laminated dark-gray to yellow clays and sandy clays bearing indurated lenses of cross-bedded, fine-grained sands cemented by ferruginous carbonate. Marine to lacustrine. Fossils: *Venericardia smithi* and *Ostrea tasex*. Overlying the basal beds occur soft and indurated gray micaceous sandstones and laminated sandy shales, with much ferruginous staining; and dark-brown lignitic shales bearing lignite and petrified wood. The lignitic shales weather to heavy black soils, but the sandy beds form light-reddish sandy clay soils. Fossils rare, except leaf impressions and silicified fossil logs. The uppermost Indio consists of laminated sandy clays and lenticular sideritic concretions somewhat similar to the basal beds, with rather plentiful fossils. Rolling topography in general; post oak and blackjack timber on the sandy soils and mesquite on the clay soils. Marine and lacustrine. Variably fossiliferous.

Midway.— 280 feet. Basal 2 to 5 feet consists of very fossiliferous glauconitic "greensand," but the overlying beds are of dark joint clays bearing "cannonball," "turtleback," and cone-in-cone concretions. Rolling topography; heavy black clay soils; dwarfed mesquite vegetation. Marine. Fossils: *Enclimatoceras ulrichi, Cucullaea macrodonta, Venericardia alticosta, Nodosaria* sp., *Cristellaria* sp., and others.

UPPER CRETACEOUS

Navarro.—500–600 feet. Base of this formation not determined. Uppermost beds consist of grayish-blue clays, with cross-bedded and evenly bedded, very fine-grained, variably indurated, light-blue calcareous sandstone weathering to a grayish-yellow color. The bulk of this formation consists of bluish-gray calcareous clays. Rolling-plain topography; heavy black clay soils; mesquite timber predominates. Fossils: *Cristellaria* sp., *Gryphaea vesicularis, Exogyra costata*, and others. Marine, principally.

Taylor.—700–800 feet. This is predominantly a clay formation, but the clays are more calcareous than those of the Navarro, the basal parts of the Taylor being highly calcareous. Sandstones and limestones are rare to absent

in this formation. Rolling-plain topography; heavy black clay soils; mesquite timber. Fossils: *Exogyra ponderosa* and others. Principally marine.

Austin.—200 feet. A massive gray chalky limestone and calcareous marl series, with marcasite concretions in the limestones. Rolling topography; stony to dark calcareous clay soils, with live-oak timber predominating. Fossiliferous. Marine.

Eagle Ford.—30 feet. Bluish- to grayish-yellow laminated shales, slightly bituminous, with thin, hard, gray lenticular flagstones. No distinctive topographic expression. Fossils: shark teeth, and others. Marine to lacustrine.

COMANCHEAN CRETACEOUS

Buda.—30 feet. A hard, dense, semi-crystalline, gray-to-dark-gray limestone. Occupies crests of some Del Rio hills on the Edwards Plateau. Fossiliferous. Marine.

Del Rio.—50 feet. A series of massive, laminated, bluish pyritic clays weathering yellow. Forms treeless slopes on Buda-capped hills on the Edwards Plateau. Fossils: *Exogyra arietina*, *Gryphaea mucronata*, and others. Marine.

Georgetown.—50 feet. Rather massive grayish-yellow limestones, forming rolling upland topography timbered with cedar and live-oak. Weathers to dark and brown calcareous stony soils. Fossiliferous. Marine.

Edwards.—500 feet. Best exposure of the Edwards formation is found in Wonder Cave, San Marcos, Texas. Consists of massive, dense, gray fractured limestone bearing dark chert concretions. Fossiliferous. Marine.

STRUCTURE

The principal structures thus far recognized in the San Marcos quadrangle are normally faulted monoclines. The trends of the faults do not coincide exactly with the strike of the formations but tend to follow this direction approximately.

THE BALCONES FAULT AT SAN MARCOS

The fault which has the major influence upon the physiography of this area is the main Balcones[1] fault at San Marcos. The dip of the fault plane is southeasterly, according to surface observations along the road leading southwest from San Marcos. Proof of the fact that the downthrown side of this faulting is on the southeast is manifested by the occurrence of the Georgetown-Edwards on the northwest and the basal Taylor on the southeast side. This faulting is very complex. Southwest of San Marcos a narrow block exposing Eagle Ford and Buda rocks seems to lie between the Georgetown-Edwards and the Taylor exposures.

The strata on the southeast side of this fault zone seem to be tilted toward the southwest, since the Austin chalk, which underlies the Taylor,

[1] J. A. Udden, *op. cit.*

outcrops on the downthrown side of the fault a short distance northeast of San Marcos.

Furthermore, the vertical displacement, which is fully 300 feet at San Marcos, decreases rapidly toward the northeast with the consequence that the fault has terminated at Blanco River. The only evidence of displacement at Blanco River consists of an accentuated southeast dip in the Buda and Eagle Ford formations. However, the termination of the San Marcos fault segment at Blanco River is compensated in part by the presence of a small fault at Kyle, with Taylor on the east and Austin on the west side, and by another fault west of Kyle, with Eagle Ford on the east and Georgetown on the west side. The approximate trend of these two fault segments is north.

All the faults in the Balcones zone at San Marcos seem to be downthrown on the seaward side. Neither dip-reversals nor marked accentuations in rate of dip were observed along these faults, the dip being about 100 feet per mile toward the southeast and east except at the point on Blanco River at the termination of the San Marcos fault segment where the dips are 5° E.

THE STAPLES–LYTTON SPRINGS FAULT

This fault is located about 9⅔ miles southeast of the San Marcos fault. Its length is about 25 miles, trending approximately southwest and northeast. The downthrown side of the fault is on the northwest and the upthrown side on the southeast, the reverse of the conditions relating to the faults at San Marcos. Furthermore, the dip of the fault plane in this case is apparently about 60° NW. At Staples, the formations on the downthrown side belong to the Midway and the formations on the upthrown side belong to the Navarro, and the vertical displacement is estimated to be about 250 feet.

As full information about this fault, as well as other faults described in this paper, is not yet available, it should be remembered that the interpretations here given are subject to revision with further facts. F. H. Lahee has made detailed studies of the Staples fault segment and concludes that this fault, instead of being single, may consist of two or three parallel faults in overlapping order. The writer admits, in this case, that there may be minor changes in direction, but he does not deem such possible variations to be extensive enough to detract materially from the general concept as portrayed in this report; and, further, he recognizes that any overlapping parallel faults present are very closely spaced and are part of the main fault system.

Southwestward from Staples, the fault cannot be traced satisfactorily for more than 3 or 4 miles, because the fault transgresses northwestward across the strike of the strata and passes into an area having Navarro on both sides of the fault projection. This transgression across the strike is a persistent characteristic of the Staples–Lytton Springs line of faulting. The fault and the Cretaceous-Eocene contact intersect southwest of Staples; but, near Lytton Springs, in the northeast corner of the quadrangle, the fault has progressively transgressed to a distance of about 3 miles southeast of the Cretaceous-Eocene contact. As a consequence, the beds on the northwest side of the fault at Lytton Springs belong to the basal Wilcox and the beds on the southeast side belong to the basal Midway formation. The vertical displacement in the Lytton Springs area is about 450 feet.

This line of faulting is composed of two major segments arranged *en echelon*, the position of the Lytton Springs segment being about $1\frac{1}{2}$ miles northwest of the northeast projection of the Staples segment. The northeast projection of the Staples segment would pass through the Lytton Springs oil field,[1] thus suggesting that the small fault in this oil field is an extension of the Staples fault line. However, the surface trace of such extension is very vague, except for the fact that lower Midway greensands are exposed in the Lytton Springs oil field area where normally one would expect to find upper Midway beds. The connection between the two main fault segments is postulated to occur in the form of a bend in the main fault line at a point about 2 or 3 miles west of Lockhart, with Midway on the west and Navarro on the east side of the bend.

The southwest extension of this line of faulting probably terminates within the quadrangle; but the northeast extension is known to pass into the southeast corner of the Austin quadrangle, which adjoins the San Marcos quadrangle on the north.

Because of the comparative lack of indurated strata in the area traversed by this fault, satisfactory dip readings can be made only at a few points and in the Lytton Springs area where the basal Indio beds are exposed. However, the ease of differentiation between the Navarro and the Midway formations renders possible rather accurate determinations as to the position of the fault.

No accentuation of the rate of dip at the fault plane was observed along the southwestern portion of this fault system. However, on Dry Creek north of Lockhart, and thence northeastward, where basal Indio

[1] Collingwood and Rettger, "The Lytton Springs Oil Field," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926).

sandstone strata are exposed on the northwest side of the fault, the rate of dip increases from the normal 2° SE. to about 15° SE. at the fault plane. This characteristic is found to be common to surface faults of this type where indurated sediments are involved. No reversals due to drag were observed along this fault system. No major cross-faults to afford adequate southwest and northeast closure to any portion of this fault uplift have been found.

THE LYTTON SPRINGS OIL FIELD FAULT

Southwest of the town of Lytton Springs, about $1\frac{3}{4}$ miles southeast of the main Lytton Springs fault segment, is an exposure of greensand bearing basal Midway Foraminifera. This exposure is on the area where one would expect to find upper Midway strata, but the occurrence of this greensand suggests an uplift of lower Midway strata at this point. The distance from this greensand exposure southeastward to the Midway-Indio contact is only about $\frac{1}{8}$ of a mile; whereas the average width of the full Midway outcrop is fully 2 miles. It is reasonable to assume, therefore, that the greensand exposure in question belongs to the middle rather than to the lower Midway.

Under full cognizance of the areal distribution of the formations in this oil-field area, it is somewhat difficult to determine this uplift as due to a fault; but the drill has proved the fault determination to be correct. Furthermore, it is very probable that this oil-field fault is in reality a part of a line of minor faulting extending northeastward from the Staples segment of the major fault. The gradual widening of the Midway outcrop along the upthrown side of the main Lytton Springs fault segment from Lockhart northeastward also suggests a surface uplift in the oil-field area.

THE LULING OIL FIELD FAULT

This fault[1] is located about 8 miles southeast of Staples and about 5 miles northwest of Luling. Its length is about $7\frac{1}{2}$ miles, extending N. 35° E.; and its vertical displacement is about 450 feet. This fault traverses San Marcos River, the southwestern third of its length lying in Guadalupe County and the northeastern segment lying in Caldwell County. The fault plane dips northwesterly, and the downthrown side is on the northwest. The beds on the upthrown side belong to the basal laminated clays of the Indio, and the beds on the downthrown side belong to the sandy phase of the Indio formation directly overlying the basal beds in a normal section. The lithologic contrast between the formations on the two sides

[1] E. W. Brucks, "The Luling Field, Caldwell and Guadalupe Counties, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9 (1925), pp. 632–54.

of the fault is very marked and offers the most precise means of determining the position of the surface fault.

The strata on the downthrown side show an extensive increased dip of 25° SE. into the fault plane; whereas the dip of the strata on the upthrown side of the fault is normally southeast.

However, available cores of the Austin chalk and the Eagle Ford shale formations, taken from wells on the downthrown side and adjacent to the Luling fault planes, do not show an increased dip. By analogy to the surface condition, one would presuppose a steeply inclined bedding-plane angle to obtain in such cores. From available evidence thus far, it seems inadvisable to take for granted, in calculating fault displacements, that the steepened dip or reverse drag obtains also in the indurated beds in the subsurface. The facts that the relatively incompetent Wilcox formation is composed of irregularly alternate layers of thin beds of indurated sandstone and thicker beds of softer sandy clays and clays and that the subsurface Austin and Eagle Ford formations are composed of massive beds of competent rocks suggest a reason for the apparent disagreement between the surface and the subsurface beds in this reverse-drag phenomenon.

The elastic-rebound theory, postulated by H. F. Reid,[1] may afford a reasonable explanation of this reverse-drag phenomenon.

On the southwest end of this fault the direction changes toward the south, thus forming a cross-fault that affords closure to the uplift at this extremity. Similarly, near Joliet, at the northeast end of the uplift, a cross-fault or change in direction from northeast to east affords the northeast closure to the uplift. In addition, at the northeast end, along the road leading south from Joliet, a northeasterly dip is shown in the surface beds along the upthrown side of the Joliet cross-fault.

In general, the Luling structure is a fault uplift bringing basal Wilcox beds to the surface in an area where younger Wilcox strata would normally be exposed. This uplift is adequately closed by major faults on the northwest side, on the southwest and the northeast extremities, and by the normal basinward depression on the southeast side.

For a more detailed description of the Luling structure the reader is referred to the writer's article on the Luling field[2] and to other articles.[3]

[1] *Bulletin Dept. Geol., Univ. of California*, Vol. 6, No. 19 (1911), pp. 413-44.

[2] E. W. Brucks, *op. cit.*

[3] E. H. Sellards, "The Luling Oil Field in Caldwell County, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8 (November-December, 1924); and "The Producing Horizon in the Rios Well in Caldwell County, Texas," *University of Texas Bull. 2239* (November, 1922); also W. E. Pratt, "Oil at Luling, Caldwell County, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7 (March-April, 1923).

THE BURDETTE WELLS FAULT

Burdette Wells is located about 8 miles north of Luling and 2½ miles northeast of Joliet. A fault trending approximately S. 65° W. is well exposed a short distance south of the station. The downthrown side is on the northwest, and the fault plane dips about 60° NW. The vertical displacement of this fault cannot be accurately estimated from surface observations because the displacement is not large enough to expose strata with satisfactory horizon-markers. The strata on both sides of the fault belong to the sandy phase of the Indio overlying the basal argillaceous beds. Inasmuch as the basal Indio is not brought to the surface by this uplift, the elevation of this uplift is less than that of the Luling uplift. However, drilling data prove that the vertical displacement is about 350 feet in the subsurface beds.

This fault cannot be traced satisfactorily for more than 1 mile, but it is undoubtedly longer. Thus far, no definite closing faults have been found associated with the extremities of the Burdette Wells fault, nor can the southwest extension be definitely connected with the northeast end of the Luling fault. The existence of a thick mantle of upstream-phase Reynosa chert gravels on the uplands between West Fork and Clear Fork creeks renders it difficult by surface examinations to determine the correct relations between the Luling and the Burdette Wells structures.

As is the case with the Luling fault, the sandstone strata on the downthrown side of the Burdette Wells fault show a highly accentuated dip of about 20° NE. into the fault plane. No drag or other reversals are found associated with this fault.

THE CIBOLO FAULT

Cibolo village is located 3½ miles northeast of Burdette Wells and about 5½ miles southeast of Lockhart, on an area of middle Indio or lower Wilcox exposures. A fault trending S. 65° W. about 3 miles long is exposed a short distance north of Cibolo. The downthrown side being on the northwest, the fault plane dips northwesterly, and the sandstone strata on the downthrown side for a distance of about 800 feet northwest of the fault dip 20° SE. into the fault plane.

The beds on the downthrown side of this fault are of hard and soft gray sandstones very similar lithologically to those on the downthrown side of the Luling fault, but their stratigraphic position is higher. The beds on the upthrown side of the Cibolo fault consist of sandy clays with a high clay content and semi-sideritic lenticular sandstone concretions that present a soil and topographic aspect similar to that of the basal Indio, but basal Indio fossils are absent.

The distance of this fault from the normal Midway-Indio contact is about $5\frac{1}{4}$ miles; whereas the distance of the Luling fault from the Midway Indio contact is about $3\frac{1}{4}$ miles. The vertical displacement is estimated from surface and subsurface data to be about 300 feet.

The Cibolo fault cannot be regarded as an extension of the Luling fault or of the Burdette Wells fault, but is probably a reflection of the Luling uplift.

Because the Cibolo fault trends N. 65° E. in rapid transgression across the strike onto successively younger strata, the closure on the northeastward extremity is supplied without the need of a cross-fault segment. If any closure obtains to the southwestern extension, the proof is not available. Much cover occasioned by a mantle of soil and upstream-phase Reynosa gravel extending from Cibolo southwestward toward Joliet renders it difficult to determine satisfactorily the true characteristics of the southwestward extension of the Cibolo fault.

THE DALE STRUCTURE

Southward from Dale, and about $4\frac{1}{2}$ miles northeast of Cibolo village, on the middle Indio outcrop, well records suggest a fault uplift of about 450 feet displacement in the subsurface Cretaceous and Comanchean limestone formations. However, no positive evidence of displacement seems to exist in the surface formations. This subsurface fault, as suggested by well records, is evidently in a position *en echelon* to the Cibolo surface fault and on the northwest side of the northeast projection of the Cibolo surface fault.

Because this area was in process of preliminary exploration at the time of the preparation of this paper, and because of the comparative absence of surface-fault indications, the writer has deemed it inadvisable to make public the detailed nature of this subsurface structure. However, it is reported that the uplifted Edwards dolomite showed the porosity generally found, contained mineralized sulphur water, and showed a faint oil stain.

THE MANFORD FAULT

This fault is located about $6\frac{1}{2}$ miles southeast of the Luling fault and directly south of the town of Luling, near Bethany Church. The trend of this fault parallels that of the Luling fault; the dip of the fault plane is 55° NW., the downthrown side is on the northwest; and the strata on the downthrown side of the fault show an accentuated dip of about 20° SE. into the fault plane. The approximate length of the fault is 3 miles. The vertical displacement is estimated to be about 200 feet, this computation

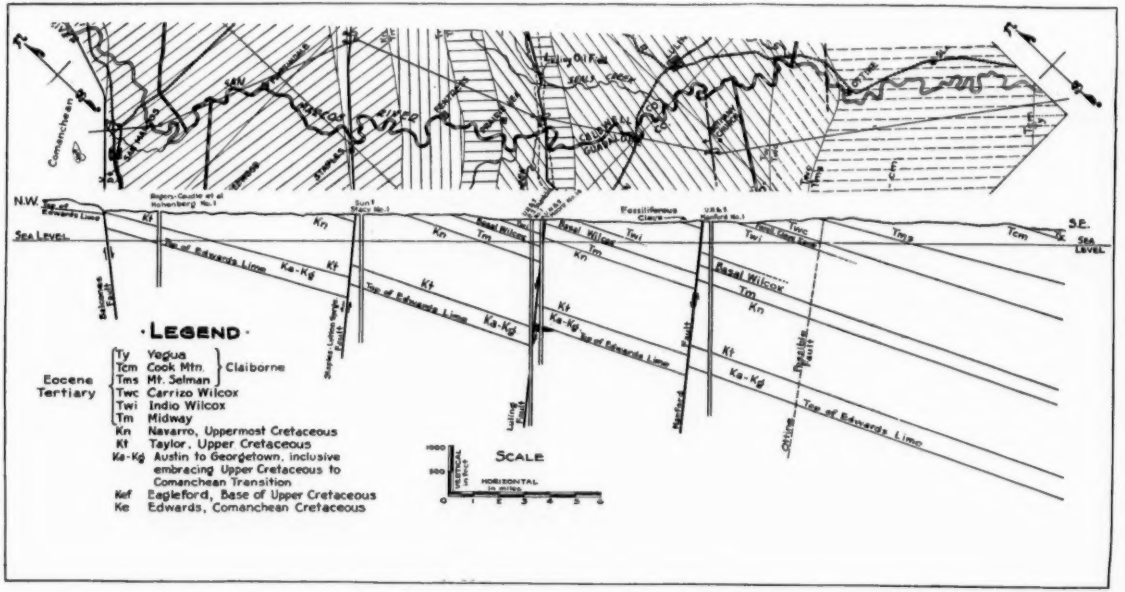

FIG. 3.—San Marcos River Valley cross-section[1]

[1] F. H. Lahee is of the opinion that the Sun-Stacy well is drilled on the downthrown side of the fault and passes through the fault plane, this opinion being based largely upon subsurface data. The writer admits that the fault may show a very slight change in direction in this locality to account for the condition suggested by Mr. Lahee.

being based upon the fact that a zone of fossiliferous clays and sandstones normally occurring at the top of the Indio section is found on the downthrown side of this fault, at a distance of about 2 miles northwest of its normal outcrop. Allowing 100 feet per mile as the normal dip, this yields 200 feet as the probable vertical displacement.

This fault cannot be traced satisfactorily northeast of San Marcos River and probably terminates approximately at the river. At its southwestern end the displacement seems to be less than opposite the location of the Manford test (Fig. 3), this being evidenced by the fact that the zone of fossiliferous clays and sandstones does not seem to occur on the downthrown side of this extremity.

THE OTTINE AREA

There is a possibility of a small fault in the Ottine vicinity, about $4\frac{3}{4}$ miles southeastward from the Manford fault. The reasons for this tentative assumption are not very conclusive; however, about $1\frac{3}{4}$ miles northward from Ottine, at Red Hill, an exposure of Mount Selman sands shows an accentuated southeasterly dip, but no fault plane exposure can be found. Because of excessive loose sand cover along the strike of these exposures, their true extent has not been accurately determined. If one considers the fact that the distance between major faults along the San Marcos River Valley decreases progressively from San Marcos southeastward (Fig. 3), and assuming that this progressive decrease in distance between faults would obtain in this case, a northeast-trending fault could be postulated to pass through this area. This area is on the approximate Carrizo–Mount Selman contact, and the steep dips occur in the basal Mount Selman beds. In this connection it may be mentioned that the prominent red sandstone scarp of the basal Mount Selman extending northeast from Ottine is a normal topographic feature caused by erosion and has no certain relation to a fault uplift.

SUBSURFACE GEOLOGY

THE SAN MARCOS VALLEY CROSS-SECTION

The cross-section of the San Marcos River Valley (Fig. 3) illustrates the structural conditions as suggested along this traverse by the surface and the subsurface geology, extending from the Comanchean outcrop on the Edwards Plateau southeastward to the Yegua Eocene outcrop.

The area between San Marcos and Staples has the aspect of a *graben* element in the form of a block tilted toward the southeast and wedged

downward between the main Balcones fault at San Marcos and the Staples–Lytton Springs fault. This tilted fault block, if such it may be called, trends northeastward from the San Marcos Valley and passes into the Austin quadrangle. Southwestward from San Marcos River, this fault block is known to extend to the vicinity of York Creek, but the southwest projection of the Staples fault segment is difficult to trace beyond this point.

The top of the Edwards is found very near the surface at San Marcos. The fresh-water springs at the source of San Marcos River issue from the Edwards limestone on the upthrown side of the Balcones fault. This formation is well exposed in Wonder Cave at San Marcos about 80 feet beneath the surface, the Georgetown being observed to outcrop at the surface. The Edwards as exposed in Wonder Cave is a hard, dense gray limestone bearing dark chert concretions. The elevation of the top of the Edwards at the edge of the Balcones escarpment is estimated to be about 550 feet above sea-level. About 2 miles southeast of San Marcos, however, at the Hohenberg test, the top of the Edwards was encountered at the depth of 615 feet, or about 25 feet below sea-level. On the downthrown side of the Staples–Lytton Springs fault, the top of the Edwards was encountered about 1,100 feet below sea-level at Staples and about 1,650 feet below sea-level in the Lytton Springs vicinity.

The Edwards in the Hohenberg test and in all other tests southeastward from the main Balcones fault is a fairly soft, brown, porous dolomitic limestone very different in character from the hard, dense, fractured gray limestone found in the Edwards formation at Wonder Cave and surface outcrops. Whereas the Edwards on the northwest side of the main Balcones fault carries large volumes of fresh water, the dolomitized lime of the subsurface Edwards southeast of this fault generally carries highly mineralized artesian water charged with hydrogen sulphide and is not known to carry fresh water southeast of this fault anywhere within the San Marcos quadrangle. In the Luling oil field, this porous dolomitized lime carries oil and gas and the usual mineralized sulphur water below the oil and gas stratum. It is of interest to note that the Edwards in the Hohenberg test flowed highly mineralized, hydrogen sulphide-charged water, whereas the uplifted Edwards at the source of San Marcos River flows large volumes of normal fresh water.

The thickness of the Cretaceous sediments overlying the Edwards seems to increase slightly southeastward from San Marcos. A notable illustration of this thickening toward the southeast is seen in the intervals between the top of the Austin and the top of the Edwards formations. In

the Hohenberg test, the thickness of this interval measures about 325 feet; whereas in the Luling oil field area this thickness measures no less than 380 feet. A similar increase in thickness toward the southeast probably obtains in the Eocene as well as in all the Cretaceous formations involved; certainly, there is no evidence available at this time to contradict that assumption.

The uplift on the southeast side of the Staples–Lytton Springs fault is proved by well data to be fully as great as suggested by the displacement in the surface beds. Some distortion of beds observed was found

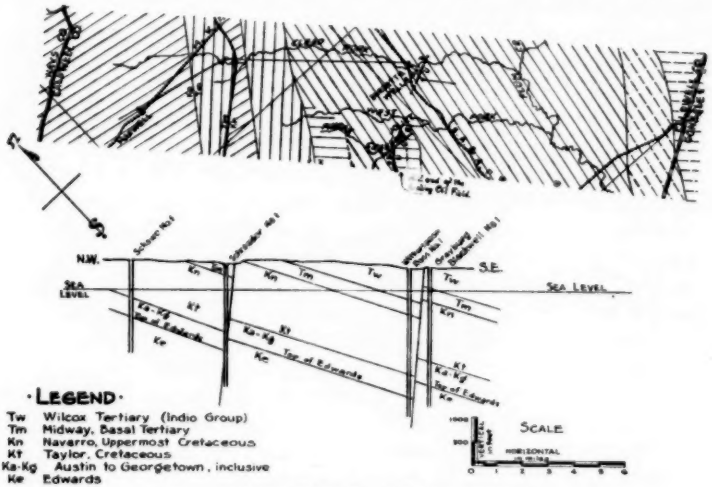

FIG. 4.—Maxwell-Burdette Wells cross-section

along the Lytton Springs segment in the lower Indio beds on the downthrown side of the fault. These Indio sandstones and sandy shales showed steepened southeasterly dips into the fault plane. This phenomenon is not extensive enough to illustrate in sections drawn to the scale of Figures 3, 4, 5, and 6. No such accentuation of southeasterly dips was observed in the Midway and Navarro clays exposed along the downthrown side of this fault line.

Southeastward from the Staples fault segment to the Luling oil field fault, the surface, as well as the subsurface, beds seem to have a normal southeasterly dip of about 100 feet per mile. At a point about 1,000 feet northwest of the Luling fault, however, the normal southeasterly dip of about 1° increases gradually to about 25° SE. at the fault plane.

Fresh artesian water is encountered in these steeply dipping Indio strata on the downthrown sides of the Lytton Springs fault segment and the Luling fault, but the Edwards carries the mineralized sulphur water generally found on both sides of these faults.

The subsurface strata below the top of the Edwards formation, including the Edwards and Glen Rose limes and the Trinity sands of the basal Comanchean, are all more or less uniformly porous and carry highly mineralized water throughout. The waters of the Glen Rose and the Trinity formations are more highly mineralized than the waters of the Edwards, the percentage of sodium chloride being much higher in the lower strata.

Underlying the basal Comanchean Trinity sands formation, which constitutes the base of the sedimentary column in the Luling area, is the basement complex, consisting of varicolored, ferruginous schists of probable pre-Cambrian age. This schist formation has been penetrated more than 1,600 feet in the Kelly No. 1 test of the United North and South Oil Company.

The area between the Staples fault segment and the Luling fault, as viewed in cross-section, has the appearance of a fault block tilted toward the southeast at the normal rate of dip; but, since the Luling system of faulting is not as extensive as the Staples–Lytton Springs system, the tilted block idea, if applicable, holds true only for the width of the sector portended by the Luling fault system. It is logical, in the opinion of the writer, to assume that the uplifts such as those of the Luling, Burdette Wells, and the Cibolo faults are caused by deep-seated uplifting forces aided by the action of block faulting.

Inasmuch as the surface strata seem to have been deposited conformably with respect to the subsurface beds, the descriptions of the subsurface stratigraphy in the Luling oil field area may be taken as a fair model for other areas within the quadrangle.

The vertical displacement of the Staples fault segment is about 275 feet, while that of the Luling fault is no less than 450 feet. It is of interest to note that the vertical displacement of the Staples–Lytton Springs fault system increases from 275 feet at Staples to about 450 feet at Lytton Springs, from southwest to northeast. In the case of the Luling–Burdette Wells–Cibolo system, however, the vertical displacement decreases from about 500 feet at Luling to about 300 feet at Cibolo, in the same northeast direction.

Although the rate of southeasterly dip of the top of the Edwards lime in the Luling field is greater than 200 feet per mile, the aggregate rate of

dip from the Luling field southeastward to the Manford fault seems to be about 150 feet per mile. There is no subsurface information available to prove that the vertical displacement of the top of the Edwards formation at the Manford fault amounts to about 200 feet, but the calculations from surface data indicate that to be the case. Furthermore, in the Manford test, the top of the Edwards was encountered lower than expected from a consideration of the normal rate of southeasterly dip.

As viewed in cross-section, the area between the Luling and the Manford faults has the appearance of a fault-block tilted to the southeast. But the more logical conclusion seems to be that the Manford fault was caused by an independent uplift having no causal relation to that of the Luling fault.

From the Manford fault southeastward, the rate of dip of the subsurface beds is assumed to be about 150 feet per mile; but, since an insufficient number of Edwards-lime tests have been made along the direction of dip in this area, no subsurface evidence exists to substantiate this assumption.

THE MAXWELL–BURDETTE WELLS CROSS-SECTION

This cross-section (Fig. 4) is located northeast of the San Marcos River Valley cross-section and traverses the area from the Navarro outcrop at Maxwell southeastward to the middle Indio outcrop at Burdette Wells. It illustrates the stratigraphic displacements occasioned by the Staples–Lytton Springs and the Burdette Wells faults respectively.

Because of the progressive southeastward transgression of the Staples fault segment to this point, a full section of the Midway occurs on the downthrown side of the fault; whereas at Staples only the basal portion of the Midway is represented. For the same reason, a narrower belt of Navarro outcrop occurs on the upthrown side at this locality than at Staples. The vertical displacement of the Staples fault segment at this point is about 250 feet, and the elevation of the top of the Edwards on the upthrown side is about 1,000 feet below sea-level.

The strata of the area between the two faults along this traverse seem to have a southeasterly dip of about 150 feet per mile. Notwithstanding the fact that the Burdette Wells fault is located fully 1½ miles farther southeast from the Cretaceous-Eocene contact than the Luling fault, the shortest distance from the Staples fault segment to the Burdette Wells fault is about the same as that to the Luling fault. This is due to the southeastward transgression of the Staples fault segment.

The vertical displacement of the Burdette Wells fault is about 350 feet, which is greater than that of the Staples fault segment and less than

that of the Luling fault. The elevation of the Burdette Wells uplift, as measured on the top of the Edwards, is about 250 feet lower than the Luling uplift; and the downthrown Edwards is about 160 feet lower than at Luling.

The Edwards formation along this traverse consists of comparatively soft, porous, brown, dolomitized lime carrying highly mineralized artesion sulphur water. Because of its soft porous texture and because it usually carries suphur water, the Edwards formation is the most satisfactory and reliable horizon-marker in determining the subsurface position of the

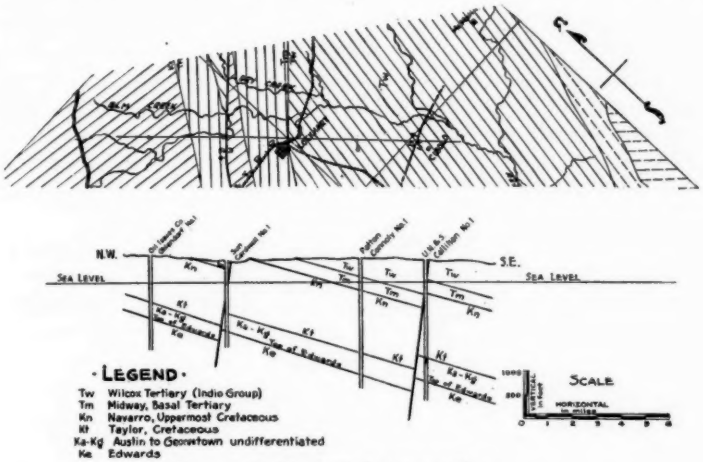

FIG. 5.—Lockhart-Cibolo cross-section

faults. The Austin formation is also a very reliable marker in the Luling area and along the Staples–Lytton Springs fault line, but in the Burdette Wells area and thence northeast the Austin formation seems to increase in thickness, and because of its softer character is hard to differentiate from the base of the overlying Taylor.

THE LOCKHART-CIBOLO CROSS-SECTION

This cross-section (Fig. 5) is located northeast of the Maxwell–Burdette Wells line. It extends southeastward from the Navarro outcrop northwest of Lockhart and traverses the Cibolo area on the Indio outcrop.

The vertical displacement and sub-sea-level elevation of the uplift due to the Lytton Springs fault segment along this traverse is practically

the same as along the Maxwell–Burdette Wells line. The Edwards formation is here, as elsewhere, porous dolomitic lime carrying highly mineralized artesian sulphur water.

The strata in the area lying between the two faults seem to dip southeastward at a normal rate of about 150 feet per mile.

The position of the Cibolo fault with respect to the Cretaceous-Eocene contact is about the same as that of the Burdette Wells fault; but the sub-sea-level elevation of the Cibolo uplift is about 100 feet lower and the vertical displacement about 75 feet less than that of the Burdette Wells uplift.

The Edwards lime in the Cibolo uplift area is of the general soft, porous, dolomitic character and carries mineralized sulphur water. The Austin lime formation as logged by drillers was found to be about 320 feet thick, or fully 140 feet thicker than at Luling. It is very probable that the upper 100 feet or so of this formation really belong to the base of the Taylor. Inasmuch as no *Gryphaea aucella* fossils were found in the core samples of this lime from the Callihan test, the exact top of the Austin cannot be determined with precision at this time.

A remarkable feature of the Austin-lime formation on the Cibolo uplift, as revealed in the Callihan test, is the fact that it is a relatively soft, slightly porous lime saturated with oil, whereas in other parts of the San Marcos quadrangle the Austin formation is a fairly hard, dense limestone formation that carries oil stains only at the top and at the base.

THE LYTTON SPRINGS CROSS-SECTION

This cross-section (Fig. 6) is located in the northeast corner of the quadrangle and extends southeastward from the Cretaceous-Eocene contact northwest of Lytton Springs to the basal Indio outcrop on the southeast edge of the Lytton Springs oil field. It traverses the main Staples–Lytton Springs fault line (or rather, the Lytton Springs fault segment) and the Lytton Springs oil field fault.

A full section of the Midway and fully 250 feet of the basal Indio occurs on the downthrown side of the main Lytton Springs fault segment, the basal Midway being exposed on the upthrown side. The vertical displacement at this point is about 450 feet, but the sub-sea-level elevation of the uplift is about 200 feet lower than at the Lockhart-Cibolo cross-section. This is due to the rapid southeastward transgression of this fault segment from southwest to northeast.

The Edwards formation along this part of the Lytton Springs fault segment is not different from the general character prevailing toward the southwest.

The dip of the strata northwest of this main fault seems to be about 200 feet per mile toward the southeast, as calculated from surface and subsurface data.

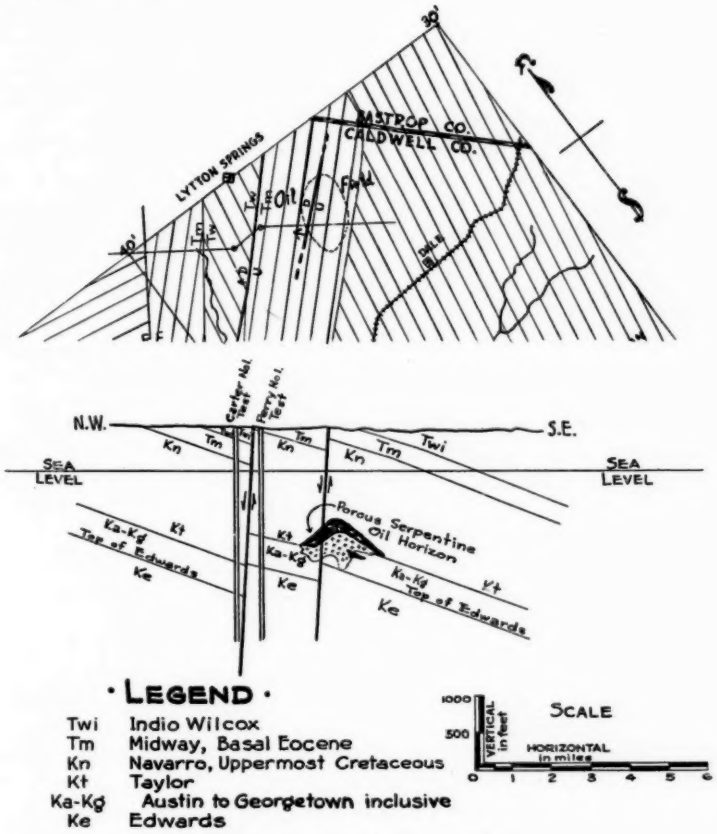

FIG. 6.—Lytton Springs cross-section

The Lytton Springs oil field fault is located about $1\frac{3}{4}$ miles southeast of the major Lytton Springs fault segment. Although the surface fault in this oil field is difficult to interpret correctly because of the somewhat confused areal relations of the surface geology, the subsurface displacement seems to be about 200 feet as based on well records of the top of the

Edwards formation. The regional southeastward dip of the strata in the area southeast of this field is estimated to be about 200 feet per mile.

The outstanding characteristic of the subsurface geology in this area is the occurrence of minutely cracked, jointed, and otherwise porous serpentine,[1] or altered basalt, in the Austin and lower Taylor formations. This serpentine body in the Lytton Springs oil field occurs in the form of a low hill of volcanic origin buried under the lower Taylor marls and clays. The northwestern edge of this buried hill occupies a position directly over the subsurface fault but does not seem to be greatly displaced by the fault.

The origin of this uplift is undoubtedly volcanic, the age of the deposit of the basaltic hill corresponding to that of the Austin formation. For a detailed description of the Lytton Springs phenonemon, the reader is referred to Collingwood and Rettger's paper[2] on this subject and to other publications.[3]

The occurrence of serpentine is reported to be widespread in the area lying in the northeast corner of the quadrangle, but other such ideal conditions of doming by a buried hill of serpentine as in this oil field have not been discovered in the San Marcos quadrangle. However, a similar condition obtains in the Thrall[4] oil field of Williamson County, Texas.

PETROLEUM RESOURCES

THE LULING OIL FIELD

This field has proved to be, thus far, the most productive oil field in that part of the Balcones fault zone lying south and southwest of the Mexia area (Fig. 1).

The production of this field from August, 1922 (the time of its discovery) to December 31, 1924, was about 14,500,000 barrels; during 1925, about 9,200,000 barrels were produced; and during 1926, about 7,809,000 barrels. The total production of the Luling field by the end of the year 1926 was about 31,509,000 barrels, and the daily production at that time was about 18,900 barrels.

The decline during 1925 and 1926 was more gradual than the normal expectation would allow. The total production by the end of 1926 was several million barrels in excess of the expectation based upon geologists'

[1] Bybee and Short, "The Lytton Springs Oil Field," *University of Texas Bulletin No. 2539* (October 15, 1925).

[2] *Op. cit.*

[3] Bybee and Short, *op. cit.*

[4] Udden and Bybee, "The Thrall Oil Field," *University of Texas Bulletin 66* (1916).

estimates made two years before. The total ultimate recovery from the Edwards oil horizon, under present-day production methods, will probably exceed 40,000,000 barrels.

The initial daily production of wells in this field ranged from 50 to 11,500 barrels, the oil being of good refining quality of gravity 27° to 29° Bé. The oil is of an asphaltic base, and yields about 55 per cent gasoline by the cracking process of refining. The top of the producing horizon is encountered at depths varying from 2,050 to 2,200 feet, in general.

THE LYTTON SPRINGS OIL FIELD

The discovery well in this field (Fig. 6) was completed in March, 1925, and came in as a 175-barrel producer of 38° Bé. gravity, paraffin-base oil. The initial production of wells ranged from 25 to 2,000 barrels.[1] The total production at the end of the year 1926 was 4,640,000 barrels; and the daily production, about 3,000 barrels. The decline of the production has been rather rapid. The depth to the top of the porous serpentine producing horizon varies from about 1,150 to 1,400 feet. The Edwards lime, occurring in normal section about 450 feet below the lower Taylor serpentine horizon, does not carry oil in this field.

THE CIBOLO AREA

Drilling on the Cibolo fault (Fig. 5) resulted in the discovery of the presence of a small quantity of 35° Bé. gravity paraffin-base oil in the Austin formation, which happens to be uniformly porous to a low degree along this fault. The top of the Austin was encountered at the depth of about 2,150 feet. The results of the test were discouraging from the production standpoint, inasmuch as the well did not yield more than 2 or 3 barrels of oil per day. The Edwards formation did not carry oil. No tests of the formations below the Edwards have been made along this fault. The oil from this horizon was not accompanied by strong gas pressure, and the oil itself is in very small volume. These facts suggest the improbability of discovering commercial production along the Cibolo fault.

THE STAPLES–LYTTON SPRINGS MAIN FAULT

This area (Fig. 2) embraces the Lytton Springs oil field fault which has been treated in a preceding paragraph. In general, the other portions of this fault area have been rather thoroughly tested to the top of the Edwards formation, but no commercial production has been obtained. However, small quantities of oil occur in the Navarro-Taylor beds south of the town of Staples, but the Edwards was found to carry only highly

[1] Collingwood and Rettger, *op. cit.*

mineralized sulphur water in this locality as well as in all other tests along this fault line (Figs. 3, 4, 5, and 6).

THE BURDETTE WELLS AREA

Several properly located tests to the Edwards formation were made along this fault (Figs. 2 and 4), but no encouraging traces of oil were found.

THE MANFORD (BETHANY CHURCH) AREA

Only one properly located test to the Edwards formation was made on this fault (Figs. 2 and 3), but no encouraging traces of oil were discovered.

THE OTTINE AREA

Thus far no tests of the Cretaceous and Comanchean oil-bearing formations have been made in this area (Figs. 2 and 3). However, gas showings and gas "blowouts" are reported to have occurred in rather shallow tests made about 15 years ago.

CONCLUSIONS

The fault systems with northwest downthrow do not seem to have the general characteristics of anticlinal uplift. There is no suggestion of extensive dip-reversals along the northwest flanks of the uplifts; instead, the landward depression is supplied by downthrow faults. If the Staples–Lytton Springs, the Luling, Burdette Wells, Cibolo, and the Manford fault systems were anticlinal uplifts subsequently faulted, some evidence of dip-reversals should show on the northwest side. On the contrary, however, there is an increased seaward dip, or reversed drag on the downthrown sides in general. The Edwards Plateau contact with the Gulf Coastal Plain in the San Marcos area seems to show evidences of having been the southeast flank of an anticlinal uplift subsequently cut by faults downthrown on the southeast. The major uplifts within the quadrangle probably owe their origin to the agencies of block-faulting in conjunction with deep-seated upthrusts rather than to folding.

The faulting occurred after the deposition of the Wilcox. Since the outcrop of the post-Wilcox strata does not show any positive evidences of faulting, it is impossible to tell whether any faulting took place during Claiborne time. In the cases of such faults as show a pronounced reverse drag, one would presuppose that the fault movement had been accomplished in a relatively short time and continuously until the present displacement had been attained.

The Luling and the Lytton Springs oil fields had produced a total of about 36,100,000 barrels of oil by the end of the year 1926.

Rather intensive wildcatting under geological direction and otherwise, both along the major faults and along traces of suspected faults and anticlines, has failed thus far to discover other than the above-mentioned oil fields of commercial importance. It is probable that new oil fields, if any are found, will be located in zones somewhat removed from those directly adjacent to the major fault lines described in this report.

The exploration for oil horizons below the Edwards formation has been carried on rather intensively in the Luling field area, but has not resulted favorably. The deep tests in the Luling area have revealed that the porosity of the pre-Edwards formations is rather uniform down to the top of the metamorphic complex and that no thick series of impervious clays exists to serve as a cap for oil horizons in the pre-Edwards sedimentaries. These factors probably apply to the whole quadrangle area and render rather gloomy the outlook for production from horizons below the upper strata of the Edwards formation.

The oil in the Lytton Springs field probably has its origin in the Eagle Ford shales, as stressed by Collingwood and Rettger,[1] although the theory that it is derived from the overlying Taylor marls is by no means untenable. Nevertheless, the only markedly bituminous formation that might have served as a source rock is the Eagle Ford formation; and this fact applies equally well to the case of the Luling field. The Luling oil, however, has a lower gravity (27° Bé.) than the Eagle Ford oil (35° Bé.); and, although the Eagle Ford is the only markedly bituminous formation either above or below the upper Edwards oil horizon, the differences in gravity suggest that other source rocks, in addition to the Eagle Ford, may have contributed to the Luling accumulation. In this connection, it may be of interest to note that the Glen Rose formation in some Luling deep tests showed a trace of very low-gravity oil. It is possible that the blending of high-gravity oil derived from the Eagle Ford and of heavier oil from the Comanchean, and the consequent ageing through several stages of geologic time in the upper Edwards reservoir, may have resulted in the formation of a grade of medium-gravity oil of the Luling quality.

DISCUSSION

C. H. Row: I wish to ask Mr. Brucks this question: "How does he explain the fact that the major faults other than the Luling fault seem to be nonproductive?"

E. W. Brucks: The most reasonable explanation I can offer is that the conditions of adequate southwest and northeast closure by major cross-faults such as those in the Luling uplift area are not satisfied in the cases of the other major faults recognized at this time.

[1] *Op. cit.*

THE ORIGIN AND SIGNIFICANCE OF "EPI-ANTICLINAL" FAULTS AS REVEALED BY EXPERIMENTS[1]

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ABSTRACT

The growth of a plunging anticline causes tension parallel and normal to the axis of the fold. Transverse fissures are manifestations of such tension, and horizontal, vertical, or pivotal movements along such fissures give rise to typical "epi-anticlinal" faults.

On short or ovoid domes such faults converge toward the locus of maximum active stress, while on the tops of longer plunging anticlines the faults are roughly parallel, but always normal to the axis of the fold. Perfectly circular domes, caused by an arrested intrusion or salt plug, exhibit a radial tension fissure pattern. Converging "epi-anticlinal" faults are regarded as due to a combination of tangential and vertical forces.

LATERAL SPREAD OF STRESSES AND RESULTING STRAINS

A very important factor which has, to some extent, been neglected by experimenters in structural geology is the attempt on the part of the sediments when subjected to compressive forces to find relief laterally as well as upward. If a pressure box is not constructed strong enough it will bulge outwardly and eventually break with too severe application of pressure. Naturally all experimenters have constructed their apparatus sufficiently strong to overcome this difficulty, and consequently, all relief of stresses in such experiments had to be *upward*. A cube of building stone unsupported on four sides and subjected to compressive stresses will fracture along planes inclined to the axis of maximum stress, forming four pyramids which will move outwardly from the axis. If the cube is supported below and on two sides by confining walls, no lateral and downward spread is possible, and the maximum relief is *upward*. In nature there are no confining walls to limit the longitudinal extent of a mountain chain or individual fold. The lateral diminution of stresses from a maximum at a given point to lesser stresses toward the margins is one explanation of the dying out of mountain chains or individual structures. Plunging anticlines are not, in most cases, the result of active stresses from four

[1] Read before the Association at the Tulsa meeting, March 26, 1927. Manuscript received by the editor, June 1, 1927.

opposing directions, but owe their existence to a maximum active pressure from one, and in some cases, two opposing sides, and a lateral diminution of such stresses (Figs. 3 and 4*B*). A perfectly circular dome does not necessarily imply stresses from four opposing directions, but may be formed by an active stress from only one side. If perfectly homogeneous materials were placed in a cylinder, such as were capable of contracting uniformly throughout its circumference, a perfectly circular dome *might* form, but such a special condition existing in nature seems highly improbable. We must seek some other explanation for the oval domes which are encountered in the field, wherever it is clear that pressure directly from below, such as caused by an arrested igneous plug or salt core, is not the cause.

In practically all the larger scale experiments performed during the course of an extensive series of investigations, a maximum pressure was usually applied at one point from one of the sides, and a varying diminution of pressure was effected laterally. In some of the experiments a rather sharp lateral diminution was effected and in consequence oval domes resulted. Upon cutting such structures at right angles to the axis of maximum stress (along the plunge of the fold) these sections revealed lateral overthrust faults. The actual relief of stresses was therefore not alone upward but also toward the sides of the apparatus (Fig. 9). An examination of the push-blocks used in some of these experiments (Figs. 5 and 6) will show that a maximum stress was active at depth and diminished upward as well as laterally, and in consequence there was formed a broad, domal uplift which was usually bordered on one side by an overthrust fault if the pressure was sufficient to cause faulting (Figs. 1*D* and 7). It is quite reasonable to conclude on the evidence and results of these experiments that some rather short, plunging anticlines and oval domes might be the result of deep-seated stresses concentrated at a point and diminishing upward toward the surface as well as laterally toward the extremities of the structure. The geological setting which could contribute to such concentration of stresses will be discussed later.

Contemporaneously with the growth of such structures, a systematic development of tension fissures takes place. The origin and significance of such transverse or "epi-anticlinal" faults is the topic under discussion in this paper.

"EPI-ANTICLINAL FAULTS" AS OBSERVED IN THE FIELD

Geological literature is full of descriptions of faults at an angle to the axes of folds such as plunging anticlines and domes. The recent detailed

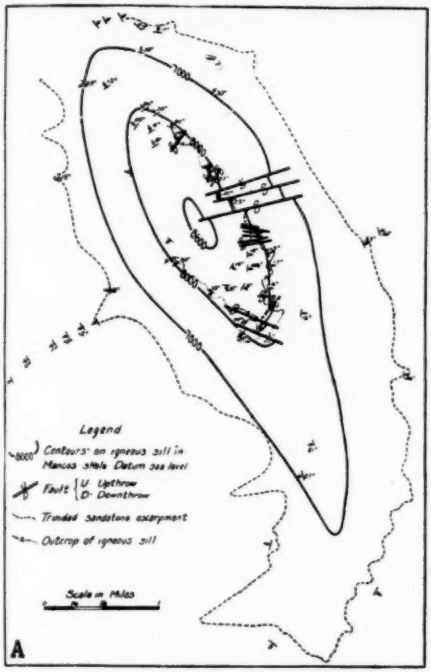


FIG. 6.—Tercio Park Dome, Las Animas County, Colorado

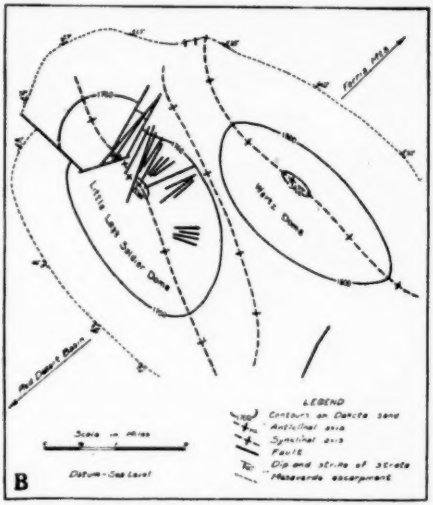


FIG. 5.—Little Lost Soldier and Wertz domes, Carbon County, Wyoming. On account of scarcity of resistant beds and extensive cover, no attempt has been made to map faults on Wertz Dome.

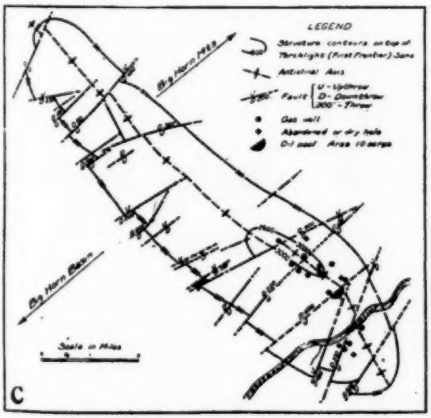
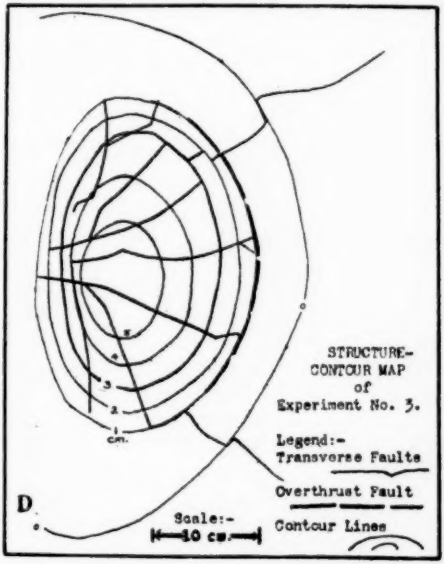


FIG. 4.—Garland anticline, Park and Big Horn counties, Wyoming



THEO. A. LINK

FIG. 1.—Anticlines and domes illustrating typical "epi-anticlinal" (transverse) faults. (Taken from Irwin.) A and are oval domes with converging fault pattern and D is a similar dome produced experimentally. C is a longer plunging nticline with the transverse faults essentially parallel.

mapping of the prospective and actual oil-bearing structures east of the Rocky Mountain front has brought out the prevalent occurrences of faults of this sort. A common way to explain their presence has been to call upon a later period of deformation which supposedly occurred after the formation of the dome or anticline. In the writer's opinion the explanation of these faults serves a double purpose. The first is to indicate the *cause* of the faults themselves, and the second is to furnish evidence regarding the direction of the actual active stresses which caused them. Most certainly an undeniable proof of the direction of active stresses in a given area will contribute toward a better understanding of the theories of orogenic movements. In consequence, the principles set forth herewith may have a far-reaching effect.

J. S. Irwin is apparently the first to give a reasonable explanation of the "epi-anticlinal" faults as found in the foot-hills belt of the Rocky Mountains. The following quotations are from Irwin's paper,[1] and Figure 1 represents several illustrations from the same source.

> The notable parallelism of epi-anticlinal faults in a given region or district, such as, for example, the Big Horn Basin and the Salt Creek–Tisdale–Teapot district of Wyoming may be explained by the fact that the majority of the epi-anticlinal faults developed transverse to the axes of the folds. Now, as the axes of the folds in the above-named region are aligned in a general northwest-southeast direction, the faults have generally northeast-southwest trends. The underlying cause of alignment of epi-anticlinal faulting in a particular district is, therefore, regional, but the evidence cited strongly suggests, if it does not prove, that the relationship between folding and faulting is genetic and, therefore, local.
>
> Just why the apparently normal habit of epi-anticlinal fault systems should be transverse to the anticlinal axis is a fundamental question and for this the writer has no explanation. In some cases the arrangement of the faults is more or less radial, with the crest of the uplift as a center. Such an arrangement, and for reasons therefor, would have been easier to conceive as the normal. The problem is apparently one of pure mechanics.

Farther on he arrives at some interesting conclusions, followed by data on the character of the faults as observed in the field.

> The mechanical effect of tension, which, at least in some cases, may be thought of as attendant upon the formation of upfolds, should not be omitted as a possible contributory cause of epi-anticlinal faulting. One example of elongation of strata involved in a fold is all that space will permit here. A section across Wertz and Little Lost Soldier domes shows an elongation in the upwarped Mesaverde sandstone of 1,000 ft. in a distance of 21,000 ft.—a little less than 5%. If we assume that the fold is of the parallel type, and draw a

[1] *Bull. Amer. Petrol. Geol.*, Vol. 10, No. 2 (1926), p. 118.

cross-section on the Dakota sand 7,500 ft. deeper, we find an elongation of 2,500 ft. in 15,000, or 16⅔%. It is not to be supposed that the resultant stretching would be anywhere near the percentages stated, due to the self-supporting effect induced by depth of burial and possibly by the moving inward of the peripheral areas under tangential forces; nevertheless it seems probable that tension is to be reckoned with as contributory to epi-anticlinal faulting.

A few of the characteristics of the epi-anticlinal faults may be noted briefly as follows:

1. The vertical displacements vary from less than 5 ft. to 700 ft.
2. Faults are known to extend to depths of 3,000 ft. in Salt Creek, and 1,500 to 2,000 ft. in Lost Soldier. How much deeper they extend is not yet known.
3. Relatively elevated or depressed blocks bounded by parallel or converging faults are common.
4. Transverse segments of folds are often shifted along the trend of the faults which bound the segments. The movement may therefore vary from horizontal to vertical, and through any combination of the two. The most noticeable result of a horizontal component (strike-slip) in the movement is offset of the anticlinal axis in the various segments. The Garland, Baxter Basin, and Little Lost Soldier anticlines are good examples.
5. The faults are occasionally pivotal, down-throw at the one end passing into up-throw at the other.
6. In some cases the faults affect the position of the oil-water contact; in others they do not.

It is very apparent that Irwin had grasped the idea of tension, and the contemporaneous development of the faults with the folding, but he failed to see the significance of what he erroneously termed the "radial" alignment, and the all-important concept which this points to, namely, the direction of active stresses toward which these faults *converge*. It is exceedingly interesting to notice how closely the descriptions of the variously observed "epi-anticlinal" faults agree with those developed in the experiments. The case seems to be clear-cut, since the theoretical analysis, the experimental results, and the facts as observed in the field are all in perfect harmony, as will be pointed out in the following pages.

"EPI-ANTICLINAL" FAULTS AS DEVELOPED EXPERIMENTALLY

If a solid cylinder is forced upward from below into a series of artificial sediments there will develop at the top of the resulting dome a series of radial tension cracks. These tension fissures will radiate in all directions from the center or top of the dome (Fig. 2). An arrested igneous mass or salt plug would give rise to such radial tension fissures.

If a cylinder into which are placed artificial sediments be subjected to compression from two opposing sides there will develop a plunging anti-

cline which will be cut by transverse tension fissures normal to the axis of the resulting structure. This is shown in Figure 3, illustrating how compression is relieved by the upward movement of the deformed materials as well as laterally by tension. In Figure 4*A* is drawn, in ground plan, an

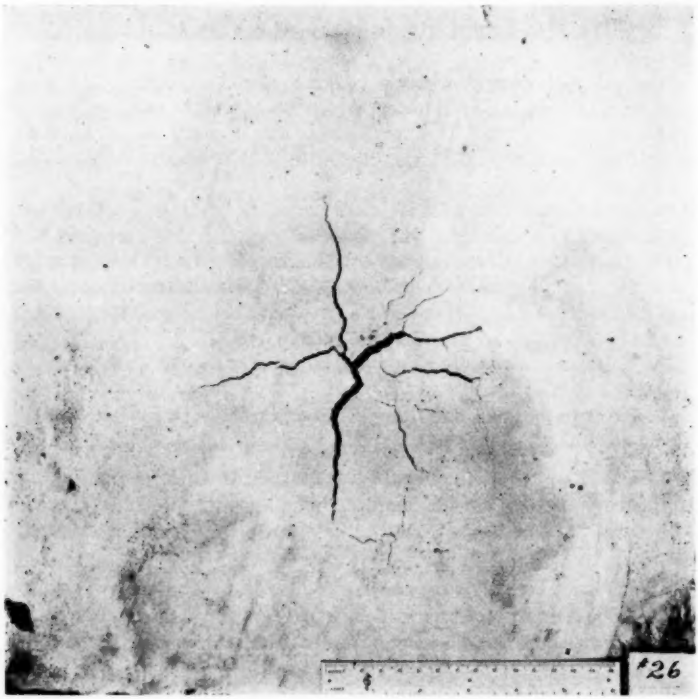


FIG. 2.—Typical radial tension fissure pattern developed on top of a dome formed by an arrested intrusion from below.

ideal case in which a rectangular push-block, *P*, which is narrower than the apparatus containing the artificial sediments, is forced against the latter. Obviously there will develop an anticline (as shown by the structure-contours) due to relief upward. Since there is an opportunity for sideward spreading, tension fissures will also develop normal to the axis of the resulting fold. In such a case as this, however, the tension fissures at the extreme ends of the fold will not be parallel to the others, because

of the bend of the axis. A case of this sort is shown in Figure 1*C* which is a structure-contour map of the Garland anticline, Wyoming.

In Figure 4*B* is drawn a plunging anticline which was developed by a push-block, whose face is that of an arc of a cylinder, *P*, forced against the sediments. Since there was no active compression from the sides it is logical to expect tension fissures, *t*, to develop transversely to the axis of the resulting fold because the anticline was stretched along its axis. Tension fissures usually develop parallel to the axis of stress; therefore, it is logical to conclude that these transverse tension cracks, *t*, will converge toward the center of the circle of which the face of the push-block *P* is an arc. The resulting fold in Figure 4*B* is an arcuate or crescent-shaped

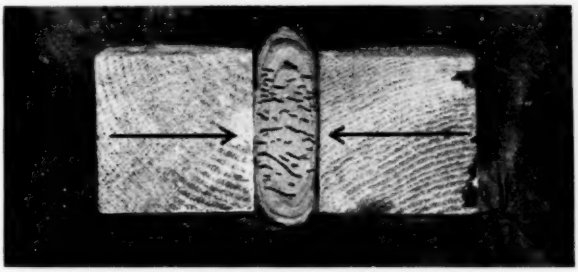


FIG. 3.—A cylinder of relatively plastic materials deformed by compression causing the formation of a plunging anticline cut by transverse tension fissures.

anticline. Figure 4*C* illustrates the probable arrangement of tension fissures in the case of two loci of maximum shortening. It is important to note that tension cracks would not develop in the recess between the two salients *P*, because active lateral compression as indicated by the arrows would prevent it.

The domes, such as those found east of the Rocky Mountain front and illustrated in Figures 1*A* and 1*B*, are by no means arcuate. Their shape is ovoid or like that of a turtle's back. They suggest very strongly stresses from below such as would arise from an arrested igneous mass or plug. However, the tension fissures, or "epi-anticlinal" faults, do not *radiate* from their crests, as would be expected from a straight upward push or force. They *converge* toward the western flank and are therefore only *semi-radial*. That they were once open fissures along which movements have taken place is clearly brought out by Irwin.[1] Their tendency to converge toward the southwest flank of the domes is apparent, but a

[1] *Op. cit.*

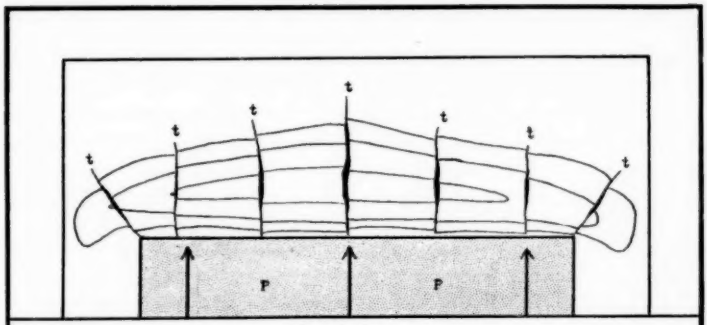


Figure 4A.

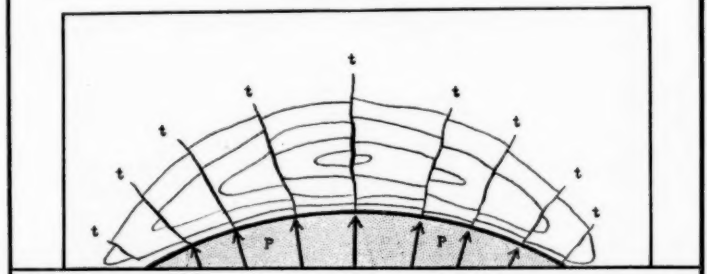


Figure 4B.

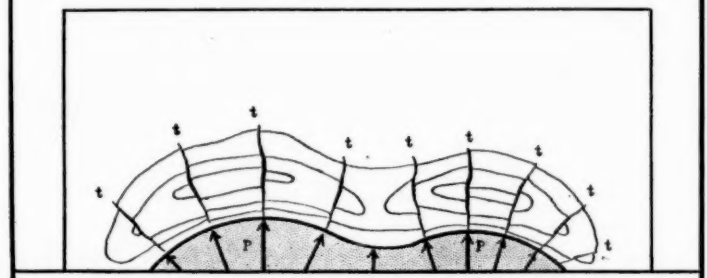


Figure 4C.

FIG. 4.—Illustrating the development of "epi-anticlinal" (transverse) faults. A, a long, straight, plunging anticline with essentially parallel transverse tension faults. B, an arcuate, plunging anticline with converging tension faults. C, a compound plunging, arcuate structure with converging tension faults. Horizontal, vertical, and pivotal movements along these tension fissures give rise to displacements and tend to straighten such faults.

true *radial* alignment is lacking. Here, then, is a condition which suggests stresses from below (the almost circular or ovoid shape of the domes) and lateral compression (the tension fissures converging toward the southwest). A comparison of Figures 1*A* and 1*B* with Figure 1*D* suggests a similarity of origin. It appears quite logical to suggest that domes of this description are the result of stresses which had a strong upward as well

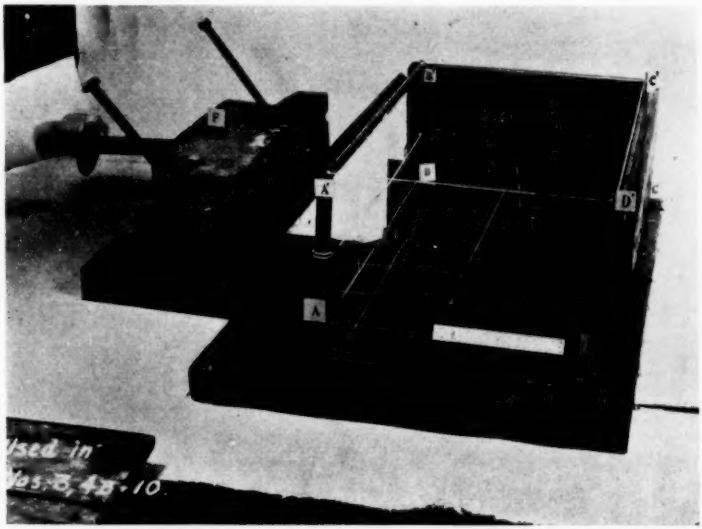


FIG. 5.—Illustrating the apparatus and method of applying pressure which gave rise to "turtle-back" domes. Movable buffer *E* is held by a hinge at the top, and is forced against the side *AA'-BB'* which is composed of a flexible fiber-rubber sheet so as to adjust itself to the shape of the buffer. Position before application of pressure.

as a tangential west-east component, the latter diminishing rapidly north and south. In other words, these domes are the result of relatively deep-seated stresses acting at an angle of about 45 degrees and dying out laterally.

The push-blocks which gave rise to domes such as those pictured in Figures 1*D* and 7 were of such shape and were forced into the artificial sediments in such a manner as to cause a concentration of stresses at depth with a diminution of stresses toward the surface as well as laterally. An examination of Figures 5 and 6, in which is illustrated the manner of pressure application, shows that the stresses were rotational and had a

vertical as well as a tangential component. The resulting broad elliptical domes are remarkably similar to those pictured in Figures 1*A* and 1*B*, and the convergence of the "epi-anticlinal" tension fissures toward the locus of maximum stresses is clearly in evidence and strikingly similar to those of Wertz and Lost Soldier domes as well as to many others in the foot-hills area of the Rocky Mountains.

In the Garland anticline (Fig. 1*C*) stresses were evidently equally

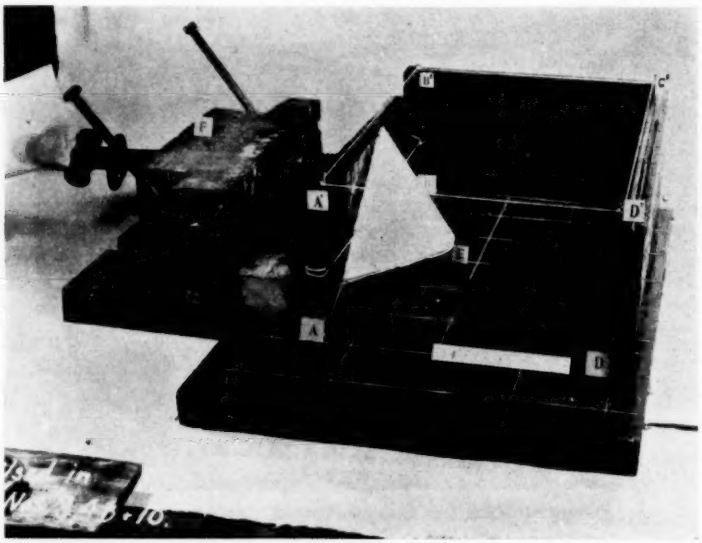


FIG. 6.—Same as Figure 5 after application of pressure. A maximum shortening is effected at *E*, whence it dies out upward and laterally. The squares represent 10×10 cm. The sides are removed partially to reveal the buffer.

distributed for some distance along the flanks of the fold and then died out rather suddenly to the northwest and southeast somewhat as in Figure 4*A*. In consequence the transverse faults do not exhibit convergence, as in the short ovoid domes.

Conditions which might have given rise to such stresses in the foothills belt are not difficult to picture. Stresses were certainly transmitted beyond the Rocky Mountain front proper, and their transmission was primarily through the deeper-lying ancient massives. The stress-transmission was undoubtedly differential when considered in a horizontal plane, since lateral variation of sediments is a condition to be expected

and not the exception. The conception of deep-seated stress-transmission is only relative and is applied with respect to the total thickness of the less resistant Mesozoic rocks and not with respect to the Rocky Mountain

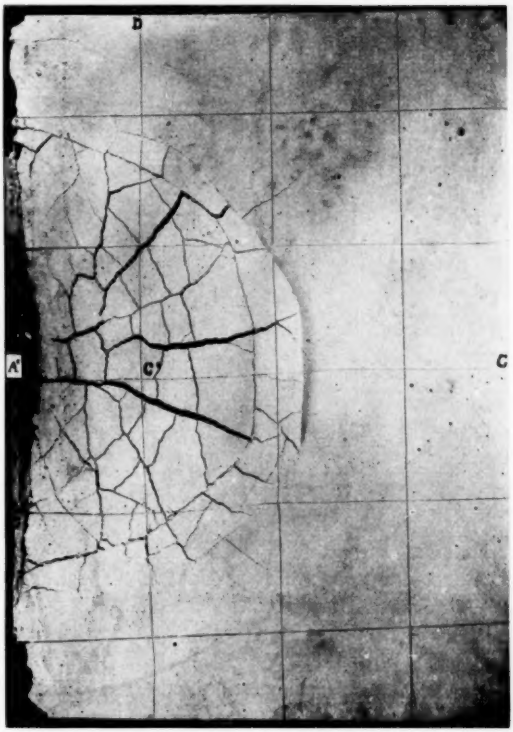


FIG. 7.—Ground plan or top view of dome resulting from application of deep-seated stresses diminishing upward and laterally as explained in Figures 5 and 6. Notice the "turtle-shaped" dome cut by converging tension fissures as well as concentric breaks. *A'–C* and *C'–D* show the position of the sections cut through the model and illustrated in Figures 8 and 9. The squares measure 10×10 cm. Pressure was applied from the left.

orogeny itself. Thus the stresses transmitted from the west had a vertical as well as a horizontal component, the average of the two being about 45 degrees, and such conditions are, according to the experimental evidence, capable of giving rise to domal uplifts with tension fractures converging toward the locus of maximum stresses.

Horizontal or vertical movements or combinations of both could easily

take place along such transverse fissures and thus give rise to normal, high-angle thrust, pivotal, or horizontal faults as described by Irwin. In some of the experiments such movements were actually observed.

TRANSVERSE FLAWS

Up to this point the evidence substantiating this conception of parallel and converging transverse tension faults has been drawn from minor structures only. The next step is to look for similar phenomena in the mountain chains themselves. Unfortunately there is not enough detail

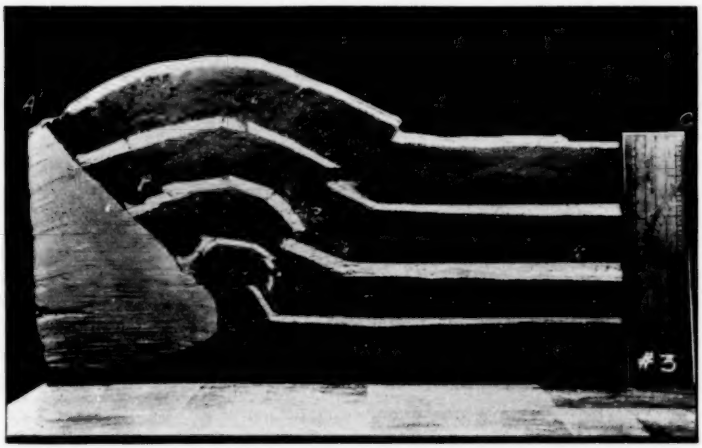


FIG. 8.—Cross-section A'–C cut through model shown in Figure 7. Position of movable buffer shown on left filled in with plaster of Paris. The scale on right is 15 cm.

work published on many of the mountain ranges which might exhibit such faults. The Appalachian Mountains cannot very well be used because of their age and profound denudation, and the Rocky Mountains have not been studied in enough detail nor have they been treated as a unit. The Jura Mountains of Europe are, however, a good example. The relatively recent age of this mountain chain makes it an ideal case and the very detailed maps bring out many transverse faults or flaws. The real significance of these faults was already noted by Heim many years ago.[1]

Plate XX of Heim's book, which is a tectonic map of the Jura Mountains, shows transverse faults or "flaws" which converge toward the direction of Lake Geneva. The descriptions of these faults are essentially the

[1] Albert Heim, *Geologie der Schweiz*, Vol. 1 (Leipzig, 1919), pp. 623–26.

same as for the "epi-anticlinal" faults. Their mode of origin is regarded as analogous. The Lake Geneva salient, caused by a localization or further transmission of stresses, undoubtedly is the reason for the arcuate shape of the mountain chain and the faults or flaws, since they converge toward that salient. The forces which built the Jura Mountains must, in consequence, have had their origin to the southeast. The general idea of their origin differs from that applied to "epi-anticlinal" faults in that

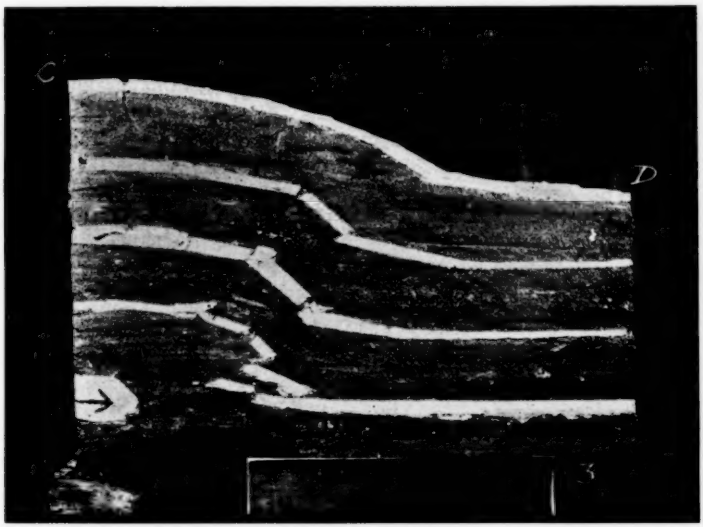


FIG. 9.—Section *C'–D* cut parallel to the axis of the dome shown in Figure 7. The white mass at the bottom on the left is the tip of the movable buffer.

the former were formed by surficial stresses but with the lateral diminution of stresses again in operation as illustrated in Figure 4*B*.

In other mountain ranges the transverse river valleys probably indicate roughly the position and alignment of such faults, since it is reasonable to assume that immediately following, or contemporaneous with, the uplifting or upfolding of a range, erosion will set in and master-streams will develop along the tension fissures which are being formed. The case might be stretched to its limit in imagining that some of the transverse master-streams of the Appalachian Mountains are not entirely a matter of superposition, but a direct consequence of transverse faults or flaws, which might date back to the first Appalachian revolution or to the

later Cretaceous doming of the peneplaned surface. The transverse dikes so strikingly developed in the Scottish Highlands may also be closely related to tension fissures.

CONCLUSIONS

In conclusion, since tension fissures develop normal to the axes of folds, it might be stated that their alignment should be as follows:

1. On arcuate or crescent-shaped folds they should converge toward the concave side of the structure.

2. On essentially circular domes which are due to pressure from below, as in the case of an arrested igneous or salt plug, there should be a radial pattern.

3. On turtle-shaped, ovoid domes or short plunging anticlines they should converge toward the side of the structure from which the active stresses came.

4. On long, essentially straight, gently plunging anticlines the fissures should be parallel to one another.

5. Therefore, since the structures east of the Rocky Mountains exhibit tension fissures or "epi-anticlinal" faults converging approximately toward the west, it must be concluded that the stresses which caused the building of the Rocky Mountains must have acted from the west, and that all theories regarding this orogeny which postulate stresses from the east must be discarded as untenable.

GEOLOGICAL NOTES

THE SAMPLOGRAPH[1]

The writer wishes strongly to recommend the usage of what he has termed "the samplograph" for purposes of subsurface correlations. It first came to his attention in the geological department of the Tidal Oil Company, and was originated by H. S. Thomas, of that company, he having first used it about two years ago at Rolla, Missouri.

This method combines the ordinary columnar well log with the actual cuttings of the rocks from the well, which are pasted on the log. The form is printed on postcard grade of paper, with the usual descriptive heading at the top. It is scaled to 10 feet per inch, with cross-lines for each foot of thickness, and has a width of one inch; each 10-foot interval contains stronger lines and consecutive numbers, from 10 to 90, in order to facilitate the construction of the log. The forms are in lengths of 3 feet, which can be pasted together to any desired length. On these forms the samples are attached by vegetable glue so that a comparison of logs can be made by having the actual well samples for observation on a uniform scale. This permits comparison of color, fracture, hardness, and all other variations in the nature and content of the materials. It is a great improvement over comparison by bulk samples, since the latter represent varying thicknesses, which makes for confusion in detailed correlation. On the samplograph one gets a bird's-eye view, so to speak, of long sections of two or more logs, and picks up the entire features or total expression of each on the same scale. The samples should first be re-washed to remove dust and coatings of mud. In this connection it should be recalled that the iron water-barrel on the derrick floor usually contains muddy water and considerable iron oxide; white sands and limes retain a film of this water, and the samples on drying may turn a reddish or brown color due to the oxides from the barrel, so that in some cases they may not retain the natural color. Very dark shales are often of a gray color from a film of dust and mud, which should be removed.

In Tulsa, the Mid-West Printing Company can furnish the log forms,

[1] Late information from George B. Corless, of Houston, indicates that Victor Rakowsky first used this method at Miami, Oklahoma, for the Picher Lead Company; and A. W. Weeks writes that he used it in 1924 at Billings, Montana, and described it in *Economic Geology*, Vol. 20, No. 7, p. 693, in 1925.

and Higgins Vegetable Glue, in half-pound cans, is used for mounting the samples. A small brush is used to apply the paste to the form, the method being to put on paste sufficient for the interval covered by the particular sample and then sprinkle the cuttings on the paste and use a short straight edge, such as a small triangle, to push the samples into proper position at the edges; the paste dries quickly and adheres strongly.

The logs, if unusually long, can be filed by suspending from a wire or string across the side of the room, perforating the top and using a paper clip. As a rule, only the deep strata will be used; 500 feet of samples will be 4 feet 2 inches long. Due to the unconformities that are encountered in Oklahoma below the Oswego lime, together with the attendant variations of thicknesses due to erosion, etc., this method of comparison is extremely satisfactory. Moreover, the logs can be shuttled back and forth under a compound microscope for a study of the materials, such as fossils.

At the last annual meeting of the American Association of Petroleum Geologists, T. E. Weirich, of the Tidal Oil Company, exhibited a samplograph of the deep beds in the Seminole field by throwing it on the screen and sliding it through a reflectorscope; this greatly enlarged the samples in their natural colors and to scale. Such usage is particularly adapted to the class and lecture rooms in the universities. Various divisions of the time-scale could be sampled and exhibited in this manner, together with characteristic fossils of each formation. It might be used effectively also in the correlation of core samples to determine shallow subsurface structure. Samples could be taken of the cores, then crushed and properly distributed on the logs, so that the entire material could be preserved and compared to scale. This could be done in the field at the core-drilling rig, while each hole is being made, and each samplograph then taken to the office. This method would be much more reliable than attempting to describe and roughly color the logs to agree with the drillers' descriptions, and would probably result in more accurate correlations, especially so in the Red-beds country.

JAMES H. GARDNER

TULSA, OKLAHOMA
June 8, 1927

SYMBOLS FOR DIP AND STRIKE

Dip and strike of the formations are generally marked on geological maps by the symbols shown in Figure 1.

The amount of dip, in degrees, is generally added to the symbol in order to have an exact record on the map of all the field observations.

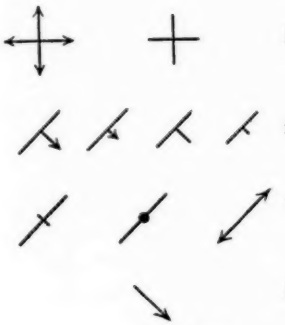


FIG. 1

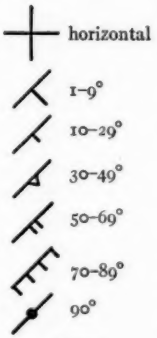


FIG. 2

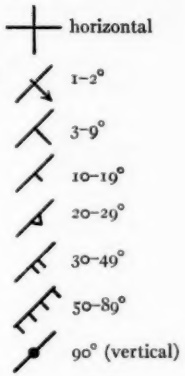


FIG. 3

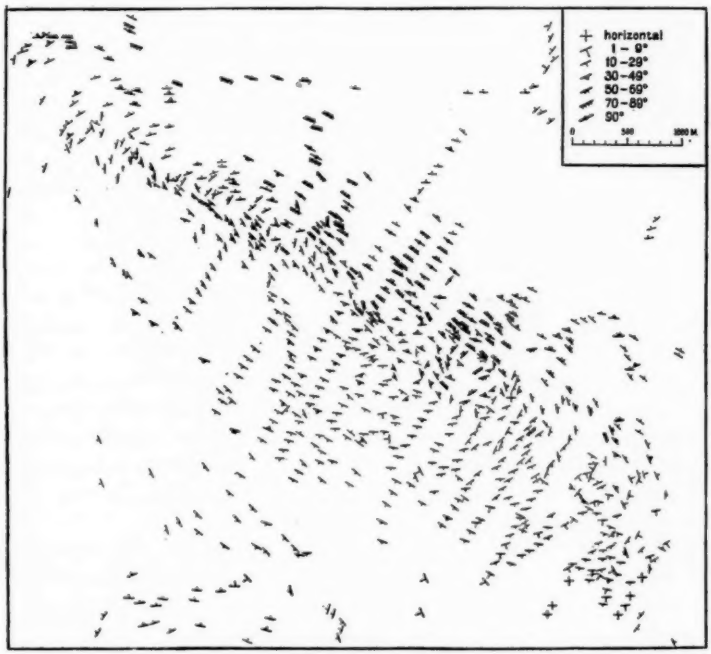


FIG. 4.—Map of dome showing dips only

In case there are very many dip symbols on a map, the figures of degrees do not permit a clear picture of the tectonic conditions at a glance. Symbols without the figures of degrees may be arranged nicely with their short strike lines, giving the impression of contour lines. This is especially the case if large-scale maps with very many dip symbols are reduced to a smaller scale.

The original maps of field geologists generally contain very many details, making it difficult to study the map effectively from a tectonic point of view. It is therefore necessary to redraft the maps, taking from the originals only the dip symbols, the wells, and as little topography as possible, reducing at the same time the large-scale maps to a smaller scale. These small-scale maps (general maps) enable the geologist better to elucidate the tectonics, as he can take into consideration more easily the conditions of the surroundings and their local influence.

The tectonic picture of these small-scale maps becomes very much clearer if different dip symbols are used for the various inclinations. The symbols shown in Figure 2 are used by the author with success.

In those districts where formations are dipping very gently and dips of 20–30 degrees are considered as "steep dips," the symbols shown in Figure 3 are used:

In Figure 4 an example is given of a map of a dome showing only the dips.

O. DREHER

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NOTES ON GEOLOGY AND STATUS OF DEVELOPMENT OF SEAL BEACH AND ALAMITOS AREAS, CALIFORNIA

The Alamitos and Seal Beach fields are located in Los Angeles and Orange counties between the Signal Hill and Huntington Beach fields in southern California. The developments in this area have now reached a point where it is possible to arrive at fairly definite conclusions regarding the controlling structure and probable areal limits of production from the two oil zones which so far have been discovered.

The structure of the area consists of two distinct domes. The Seal Beach dome, which is the southeastern of the two, was proved productive by the completion of Marland Bixby No. 2. This is an elongated dome the axis of which trends about N. 45° W. The highest point on the structure is located about 1,200 feet south of the north quarter-corner of Sec.

11, T. 5 S., R. 12 W. The axis of the structure plunges northwest about 5,000 feet to the structural saddle which separates the two domes. This saddle is at least 170 feet lower structurally than the high point of the Seal Beach dome. It is possible that production may be found to extend most of the way across this saddle. The southwest flank of the Seal Beach dome has a dip of about 8°. The southeast plunge is about 6° and has been determined for a distance of about 2,000 feet from the high part of the structure. The nature of the northeast flank of the structure is not definitely known. There is topographic evidence in Landing Hill, which is corroborated by subsurface evidence in Marland Bixby No. 1 and Associated Bryant Nos. 21 and 31, for the existence of a nearly vertical fault trending N. 48° W. in the vicinity of these wells. The vertical displacement of this fault is about 200 feet in the vicinity of Associated Bryant No. 21, with the north as the downthrow side. Whether or not this fault will mark the northeast limit of production is not yet determined, but the number and distribution of the dry holes on the northeast side of the fault make it seem improbable that any extensive area of production will be developed in this area.

The more recently discovered Alamitos dome is situated on the northwest prolongation of the axis of the Seal Beach dome. The high point of this structure is about 70 feet lower than the high point of the Seal Beach dome. It was proved productive by the completion of Pan American Naples No. 1. The Alamitos dome is very nearly circular in shape and is separated from the Seal Beach dome by the structural saddle previously mentioned. The southeast closure is at least 100 feet. The structure of the northeast portion of the dome has not yet been determined definitely, nor has it been determined whether or not the fault which is thought to exist on the northeast side of the Seal Beach dome continues through the northeast side of Alamitos dome, although there is some topographic evidence to indicate that it does.

Wells in this area penetrate gravel beds to depths of 1,200 and 1,500 feet, possibly representing the late Pliocene and Pleistocene sediments. Below the gravels the beds consist of a series of irregularly alternating sands and shales of Pliocene age. Sandstone members range in texture from medium to coarse, and in some places are true gravels. The shales also differ in thickness and hardness and show irregular or rhythmic alternating laminae, or commonly a gradation from sandy shale to true shale. Foraminifera are common. Decomposed wood and carbonaceous material generally associated with mica are common. The oil occurs in sand members between interbedded shales.

Up to the present time practically all the oil has been produced from

two zones. The upper zone is called the Bixby zone, but is not necessarily the equivalent of the Bixby zone of the adjacent Signal Hill field. The lower zone is called the Selover zone, and its top is found with considerable uniformity 225 feet below the top of the Bixby zone. The Bixby zone contains a greater proportion of shale than the Selover zone, which is predominantly sand. In addition to and above these two productive zones there is a relatively thin zone containing oil sand which has not been tested in the structurally higher portion of the Seal Beach dome. Recently a new productive zone has been discovered by Wasem No. 7 of the General Petroleum Corporation. This well is situated beyond the productive limits of the Selover zone. The top of the new zone is approximately 400 feet below the top of the Selover zone and has been penetrated only 23 feet. The total thickness of this new zone has not been determined, but its lateral extent is obviously greater than that of the Selover zone. With the extremely rapid declines of the wells in the Selover zone, it is probable that many of the wells now producing will be deepened to the new zone. In some parts of the field the present spacing of rigs is so close that there is not sufficient space for new rigs, and any drilling for the new zone must be by the deepening of wells now in the Selover zone. No favorably located well has yet been drilled deep enough to test the possibility of this zone, or of any additional oil zones below.

Production in the Seal Beach field is obtained from both the Bixby and Selover zones, but the production in the Alamitos area is confined to the Selover. High showings above the Selover zone have been noticed in the drilling of several wells in the Alamitos area, and there appears to be a possibility that the Bixby zone may be present and capable of production in the structurally higher portion of the Alamitos area.

The thickness of beds containing oil sand differs in each of the zones, depending on position on the structure. In the higher portion of the Seal Beach field the Bixby zone contains oil sand through a thickness ranging from 160 to 204 feet, but this thickness decreases in the wells farther removed from the crest of the structure, and wells on a contour 150 feet below the high point of the structure penetrated only a very few feet of oil sand in the position of the top of the Bixby zone. A similar condition exists in the Selover zone in both of the fields. The greatest thickness of the Selover zone to be taken by any well has been 295 feet. Wells situated below the −4,650 contour, that is, more than 50 feet structurally lower than the top of the Alamitos dome, encounter an intermediate edge water in the Selover zone. Several wells have casing set below this water to produce the lower portion of the zone.

Many of the wells which were originally brought in with 15–20 feet of open hole below the shoe of the water string have been deepened in the Selover zone. These deepening operations and the completion of later wells to include 100–295 feet of the Selover zone have increased the production of the Alamitos area. The estimated peak production for the Selover zone in this area is between 48,000 and 55,000 barrels a day.

The Seal Beach dome is controlled by three producing companies, the Marland Oil Company, Associated Oil Company, and Standard Oil Company of California. The wells in this field are drilled 300 to 500 feet apart. The Alamitos dome, however, is in an area of town lots and has been the scene of an intensive drilling campaign with closely spaced wells. This area, which might support 20 wells under ordinary well-spacing programs, now contains approximately 200 rigs.

SEAL BEACH DEVELOPMENT DATA, JUNE, 1927

Number of wells drilling	72
Number of wells re-drilling and deepening	16
Total	88
Number of wells producing	77
Daily average production, week ending June 18, 1927	74,000 barrels
Total production to June 18, 1927	6,063,000 barrels

C. M. CUNNINGHAM
NORMAN HARDY

WHITTIER, CALIFORNIA
June 21, 1927

DISCUSSION

THE EFFECT OF GRAVITATIONAL COMPACTION ON THE STRUCTURE OF SEDIMENTARY ROCKS. A REPLY TO A DISCUSSION BY W. W. RUBEY

A discussion of my paper published in this *Bulletin* under the title of "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks"[1] has kindly been sent to me by W. W. Rubey. In his paper Rubey attempts to formulate a mathematical equation, based on the data published in my article, which will express the relations between pressure and porosity in fine-grained argillaceous sediments. He criticizes the writer's method of expressing the same relation based on the same data. He defends his conclusions as to the origin of the Fairport-Natoma anticline, the validity of which had been questioned by the writer. Finally he attacks the writer's discussion of the character of folds due to settling, and his general theoretical conclusions concerning the significance of pressure-porosity relations.

In a number of instances Rubey has made such misinterpretations of my statements as almost to make his remarks amount to misquotations. Moreover, the statements in my original paper which Rubey has questioned seem to me as valid after reading his discussion as they seemed at the time of writing. Consequently, I feel obligated to reply to his discussion; if for no other reason, at least to correct the distorted impression of my ideas which his paper conveys.

A brief restatement of some of the ideas presented in the original paper is apparently a desirable introduction to any discussion of Rubey's criticism. Porosities of clay and shale samples from outcrops and well cuttings were determined and similar previously published data collected. Experimental data on the porosities of clays under low pressure were also assembled. A curve was plotted to represent pressure-porosity relations in the purer fine-grained argillaceous rock types *in so far as shown by the data available*. This curve was based on no hypothetical idea of what the relations should be, but was plotted solely from what seemed to be the most dependable actual porosity data on this type of rock, and is thus merely a representation of fact. A second curve was plotted from a modification of a proposed pressure-void ratio equation developed by H. C. Sorby. This curve showed striking similarities to the first for high pressures and low porosities, but failed to agree with experimental data for low pressures. In order to facilitate calculations, a third curve was drawn in which the irregularities dependent on the nature of the first curve were smoothed into a regular curve. For high pressures this third curve was drawn to coincide with

[1] *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1035–72.

the second curve based on Sorby's relation, as this made it a regular curve without appreciably changing its value.

As should have been clear from the original article, it was not supposed that this curve was accurate for all shale, nor yet for any one shale. Neither is it possible to make such a curve, nor would it be of any practical value. An idea of the general relation between pressure and porosity and the order of magnitude of the change in the one, contingent on increases in the other, were the ends sought. With this preface I shall consider in order points which I have noted for discussion in Rubey's paper.

1. Rubey says:

> From laboratory and well data and theoretical considerations, Hedberg shows that the volume of shale varies roughly in inverse proportion to the pressure exerted upon it. Probably all readers will share his wish to apply this generalization as a test to the compaction theory of structure. However, it is his transposition of the fundamental data into a form suitable for this purpose that I consider unsatisfactory. He combines the depth and porosity determinations of well and outcrop samples and smooths these average figures into a curve to be used for all shale.

The pressure-porosity curve was not meant to be applied without modification to "all shale." It was thought to be "approximately indicative of the true *relation* between porosity and pressure *for the particular type of shale used*," but only "*roughly* so for *all* dominantly argillaceous sediments."

2. Rubey continues:

> In order to make this combination into one curve, two important assumptions are necessary: (1) That there is a fundamental depth-porosity curve which, other things being equal, all shale tends to follow as it is compressed. It should be obvious that there can be no fundamental depth-porosity curve for all shale; on the contrary every specific type of shale will have its own particular curve and there are no two beds of shale which will show exactly the same curve. However, as has been stated before, it is believed that for the particular type of shale used (sandy and calcareous shales were avoided) the curve "may be approximately indicative of the true relation between pressure and porosity, etc."

3. "Except for the Ranson well in western Kansas, Hedberg does not state what data he used for his averages nor what he estimates as the thickness of eroded rocks." The high pressure part of the porosity gradient was based largely on data from the Ranson well. The Lynn well was considered, but the difficulty of correctly estimating overburden and the fact that it was located much nearer to areas of known deformation, as was stated in the original text, made the data from this well seem less reliable. The sudden change in porosity between depths of 500 and 975 feet in itself arouses suspicion. Outcrop samples of sediments of the most recent periods together with data on freshly deposited muds and experimental laboratory data were used to construct the low-pressure end of the curve.

4. Rubey writes: "At an estimated original depth of 2,500 feet the shale from the Ranson well has about 25 per cent porosity, and that from the Lynn

well about 8 per cent. At this depth his curve shows a porosity of about 20 per cent." Reasons for considering the Lynn well cuttings less reliable than those from the Ranson well have already been given. The depth estimate of 2,500 feet overburden for the shale from the Ranson well, of porosity about 25 per cent, was made by the writer. However, there is certainly nothing in my paper that would indicate that I considered the 8 per cent porosity of the Lynn well sample as also due to an overburden of 2,500 feet, as Rubey's sentence implies. On the contrary, it is my opinion that a much greater overburden is probable, or at least entirely possible.

5. According to Rubey, the second important assumption on which the porosity curve is based is the assumption of an average initial porosity of 50 per cent for 100 feet of mud. Rubey comments: "From the observational data cited in his paper it seems that the average initial porosity might as well have been estimated at 40, 60, or 80 per cent." He then proceeds to make calculations based on the figure 75 per cent in order to emphasize the importance of the value of the assumed initial porosity.

The writer's figure of 50 per cent is in all probability subject to considerable error. However, it was carefully based on all available data, and was selected only after careful consideration of the following points:

a) The majority of the purer types of clay deposited in the laboratory gave initial porosities, for columns a few inches long, of from 80 to 85 per cent.

b) The pressure-porosity curves, constructed from Terzaghi's data, in all cases show porosities of less than 50 and more than 40 per cent for pressures equivalent to the weight of 50 feet of freshly deposited mud, allowing estimates of the average density of this mud to range from 1 to 1.9. The average porosity of the upper 50 feet of a 100-foot column would of course be much higher than the figure at a depth of 50 feet. On the other hand, the average of the basal 50 feet would be a little lower. Hence it is reasonable to suppose that an average figure for the hundred feet would be somewhat higher than the figure at a depth of 50 feet. A moment's examination of the curves based on Terzaghi's data is sufficient to show that 60 per cent would be an absurdly high average, just as 40 per cent is unquestionably too low.

c) Experimental loading of sediments in the laboratory has demonstrated the rapidity with which high initial porosities are decreased. A very pure white clay (an English kaolin) showed an initial porosity of more than 80 per cent for a column a few inches long. Overburden of less than one pound per square inch decreased the porosity to less than 70 per cent. The rapidly increasing friction which developed in the container with increase of overburden prevented the relation from being determined accurately for higher pressures, but Terzaghi's data indicate that the porosity of clays continues to decrease rapidly throughout the application of the first 100 pounds' pressure.

d) None of the data determined by the writer or collected from other sources shows a porosity of more than 55 per cent for dominantly argillaceous

material other than that freshly deposited and tested within a short distance of the surface. Data from Shaw and Lewis on recent mud deposits show porosities ranging from 40 to 90 per cent, but are based on specimens taken near the depositional surface. A weathered surface clay from New Jersey shows a porosity of 52 per cent. Sorby mentions a clay from an old lake bed with a porosity of 49.5 per cent. King places the average of numerous tests of clay soils at 45 per cent. The United States Department of Agriculture states the average of many soil tests as 55 per cent.

It is very possible that future investigations may prove the writer's figure of 50 per cent to be in error; but in the light of the data available at present it seems the best that can be chosen. The writer feels that 40 per cent is too low and 60 per cent too high; 75 and 80 per cent seem ridiculous.

6. Rubey next remarks: "True, Hedberg frankly disclaims mathematical accuracy for his curve, but these cautions seem forgotten where, farther on in the paper, he estimates his results as accurate to within less than half their computed values and recommends that these results be applied as a quantitative test to structural theories." This statement of Rubey's is inexcusably inaccurate, the more so as it practically amounts to a misquotation. Nowhere in my paper do I state that I consider my results "accurate to less than half their computed values." Regardless of any personal opinion I may have in the matter, I have reiterated throughout the paper that the curve and the figures which it represents, from the nature of their source, can be at most only roughly accurate. In my first application of the curve I even suggested modifying it by 50 per cent to more nearly conform to the lithologic character of the shale in question.

As evidence of my attitude in considering the curve I need only quote from the original manuscript:

> No attempt is made to claim mathematical accuracy for the porosity gradient previously given. A brief consideration of the material available for study, the factors controlling porosity, and the limitless variety in lithology . . . . is sufficient to show that great exactitude is impossible as well as unnecessary where application is to be general rather than specific. It is thought, however, that the table may be approximately indicative of the true relation between porosity and pressure for the particular type of shale used, and roughly so for all dominantly argillaceous sediments. The testing in detail of the accuracy of the figures here presented must await the accumulation of further data. [And also:] From analytical data a *rough* scale of the *relations* between pressure and porosity for pressures up to that produced by 8,000 feet of rock overburden has been computed.

As previously mentioned, the very fact that I have suggested modification of the curve to suit the lithology of the shales in the particular areas which I have discussed should be ample evidence that I did not consider it the perfect representation of an immutable mathematical formula. Furthermore, it is to be noted here that the fact that a part of the curve was modified by, say, 50, 20, and 10

per cent by no means implies that this is the estimate of its accuracy. From the nature of the matter under consideration the curve can never be any more than approximately accurate. It can be modified to suit obvious variations from the ideal case, but the errors inherent in the original curve are just as operative in any modification of it. Hence modifications of the original to suit variations in lithology do not increase the accuracy; they merely prevent the error from becoming larger. However, one part of the existing error is of course due to scantiness of the information on which the curve was based, and certainly decrease in this error may be expected with the accumulation of further data.

7. Rubey says:

> If the compaction theory is to be tested by his studies, it should be by some method of treatment which, though taking into consideration all laboratory and field determinations, does not agglomerate dissimilar series into a single average curve and which does not call for or weight so heavily an assumption of the initial porosity.

From the nature of the theory it is obvious that the porosity of a mud in the early stages of consolidation must be weighted rather heavily. However, it is equally obvious that it is not the porosity of mud within a few inches of the depositional surface, nor even within 10 or 20 feet, which is of importance in the calculation of the structural effects of compaction. It is only when the topographic relief on an old erosion surface and the corresponding thickness of the muds deposited there reach the order of 100 or at least 50 feet that settling has an important influence on the structure of beds any considerable distance higher in the stratigraphic column. Furthermore, the porosities of columns of mud a few inches or feet in thickness are very sensitive to pressure and highly variable, depending on the character of the mud. Consequently it is more difficult, as well as of less practical value, to estimate average porosities near the surface.

It might be expected that Rubey would himself avoid any method which would "call for or weight so heavily an assumption of the original porosity." However, on the contrary, in his own calculations he places the initial porosity of clay at 100 per cent, based on the assumption that there is a regular gradation in porosity through water-saturated muds to pure water, which he considers mud with a porosity of 100 per cent.

For the reasons previously given, in the calculation of compaction, initial porosity was not placed at 100 per cent, nor yet as the porosity of mud just below the base of the depositing medium, but rather as an average for the upper 100 feet of a freshly deposited mud column. The means by which the figure 50 per cent was reached have been explained previously. From existing data it seems that 60 per cent is too high a figure. However, even supposing that additional porosity data should prove 60 per cent to be more nearly correct, the difference in results is certainly not tremendous. A hundred feet of mud buried under 3,000 feet of sediment would theoretically be reduced to 50 instead of 60 feet, and 100 feet of shale with a porosity of 8 per cent would have had an origi-

nal thickness of 220 feet instead of 180. It is only when high initial-porosity figures are reached that the difference in calculated results begins to increase rapidly.

8. In regard to the "agglomeration" of "dissimilar series into a single average curve," let me say that if the term "dissimilar series" is used to express no broader differences than those which exist between the more purely argillaceous types of non-calcareous clays, then this was certainly one of the writer's objectives. Unless the pressure-porosity curve is to be an average it cannot exist. To consider the pressure porosity relations for every type of comparatively pure argillaceous clay or shale and thus determine the resulting compaction of a whole sedimentary series is impossible. It is not a question of dealing with a homogenous substance. Van der Waal's equation will apply equally well to all hydrogen gas, but no formula can be derived to apply exactly or even with constant error to clay or shale.

If Rubey's "dissimilar series" are the stratigraphic columns represented in different well borings, I need only ask if there is any reason to suppose that there is less variation between the character of the shales in the Pennsylvanian and Permian systems in the Phillips well, for instance, than there is between the Pennsylvanian shales of the Phillips well and the Pennsylvanian shales of the Ranson well. Apparently Rubey thinks there is, for, while he objects to applying data from one well to another with approximately the same stratigraphic column, and thinks it necessary to change his constants from one well to another, he gives no consideration to possible differences in the shales encountered by a single well, passing, for example, through several thousand feet of sediments and representing several different geologic periods.

9. Rubey says: "Sorby found that the ratio of solids to voids is a function of the pressure exerted upon argillaceous rocks, and, as shown in a following paragraph, Hedberg's well data likewise show a relation between depth and void ratio." I wish to note here that the similarity between the well data and results obtained from a slight modification of Sorby's suggested relation between pressure and void ratio had already been considered in my original paper. My statement is:

> Following Sorby's suggestion that the relation of pressure to porosity may be inversely proportional to the ratio of pore space to solid particles, assuming an average porosity of 50 per cent for the first hundred feet, and converting feet of sediment into pressure per unit area in such a way as to take into consideration the increase of density with depth, a second set of data was calculated. This plotted curve B shows striking similarity to curve A, especially where pressure is high, but fails to hold for low pressures and high porosities.

For the part of the curve on well data, in fact, the two curves practically coincide. The agreement of this theoretical relation with observational data is much less perfect where porosity is high and pressure low. Hence I concluded that while the general principle of Sorby's relation seemed applicable, it could not be

carried out as a definite mathematical expression of fixed terms throughout the whole range of pressure-porosity relations.

10. The mathematical expression which Rubey uses for pressure-porosity relations, based on laboratory data assembled in the original paper, is interesting, and it may be added that its validity is to be expected on theoretical grounds. In the early stages of compaction, such as are represented by Terzaghi's and the writer's laboratory data, reduction of pore space is accomplished chiefly by the expulsion of adsorbed water, as was noted in the original paper. Freundlich has shown that in the case of gases the relation between pressure and adsorption may be expressed by the equation:

$$\left(\frac{x}{m}\right)^n = kp$$

where x is the quantity of gas adsorbed, m the amount of the adsorbing solid, and p the pressure of the gas, while k and n are experimentally determined constants which vary with the temperature. It may perhaps be assumed that this type of equation may apply equally well to the adsorption of liquids. However, in the clay-water system of the laboratory experiments, pressure is exerted on the solid while the liquid is free to escape. Consequently, the process is almost the exact reverse of that represented by Freundlich's equation. Now if the pressure symbol p be changed to its inverse value, the equation thus becomes

$$\left(\frac{x}{m}\right)^n p = k \ ,$$

which is identical with Rubey's equation

$$L\left(\frac{P}{100-P}\right)^m = K$$

where L is the equivalent of p, P of x where pore space is filled with water, and $100-P$ of m.

It is to be noted that in the one case the values of the constants vary with the nature of the adsorbing substance and the character of the gas, just as in the other they vary with the type of clay and the character of the depositing medium. The range of this variation is great in the case of gas-solid systems. That it is also great in the case of clays and water, the values of Rubey's constants have amply demonstrated.

While the equation seems theoretically valid, it is my opinion that the experimental data at present available do not warrant the acceptance of a specific formula to express pressure-porosity relations of even "the finest-grained sediments under natural conditions," although Rubey believes that the inference

seems warranted that for these sediments the value of m is less than 5. The values which Rubey finds, using the published data, range from 5 to 80.

11. Rubey says that I "recognized that in nature the porosities would fall off more readily than they do in the laboratory experiments—that is, in nature the exponent m would have lower values." It is true that in nature porosity may be decreased more readily by rearrangement of particles toward maximum compactness, but this is not directly a pressure effect and cannot legitimately be allowed to influence the exponent m. It is also true that more time for settling is available in the case of natural sediments than in laboratory experiments. However, it is worth noting that in my experiments—which for pressures of less than one pound per square inch must indeed very closely have simulated nature—the English kaolin at one time stood for months under a pressure of only a few hundred grams without appreciable change in volume.

12. In regard to the comparative accuracy of Terzaghi's experiments and my own, I wish only to correct Rubey's inference that the effect of time was considered only in the case of the first-mentioned experiments. Terzaghi allowed two days' time for restoration of equilibrium after each increment of pressure. I mention a period of "a few days" in respect to my data. This period was usually from 3 to 5 days.

13. From a consideration of the porosities of well cuttings assembled in my paper, Rubey concludes that the expression

$$(D+B)\frac{P}{100-P}=C$$

expresses the relation of pressure to porosity. Rubey has noted that this is "but a slight modification of the theory proposed by Sorby . . . . that in argillaceous rocks the ratio of solids to voids varies with the depth." Rubey shows the similarity of results calculated by this formula to the data on the Ranson well, and I have previously shown the similarity of Sorby's relation, modified by my assumption of average initial porosity, to the Ranson well data, and have expressed the opinion that beyond the range of the Ranson well data "further reduction of pore space increases approximately in proportion as the ratio of pore space to solid particles in the rock diminishes." It seems that the relations between pressure and porosity at depths as great or greater than those of the Ranson well cuttings may thus be approximately expressed by some such formula as Rubey proposes.

14. However, Rubey now attempts to show that his equation based on laboratory data may be correlated with the equation for the Ranson well data; that the exponent m in the first formula "should be somewhat more than one for moderate loads," which "accords with the conclusion, based upon consideration of the accuracy of laboratory experiments, that it should be less than 5; and finally that the two equations express approximately the same relations between load or depth and void ratio. He then proceeds to use the one formula derived

from the well-cuttings data in calculations covering the whole range of the porosity gradient.

The fallacy of this correlation might be expected from theoretical considerations. It is at once apparent from the difference between the graphical representation of my modification of Sorby's relation and the curve based on actual data. Finally, the attempts to put the correlation in practice result in absurdity.

Rubey has noted the similarity of his second equation to Van der Waal's expression, and the writer has suggested previously the possible analogy between Rubey's first equation and Freundlich's adsorption isotherm formula. As was stated in my original paper, "the first stage in the compaction [of muds, clays, etc.] is marked chiefly by elimination of excess pore water and dehydration of colloids, accompanied by a rearrangement of particles toward a mechanical structure of maximum density." Further compaction is accomplished by deformation and granulation of soft and fragile particles. The pressure-porosity curve thus represents two different physical processes which are represented by different mathematical expressions. While there is probably not a sharp division line which marks the change from one to the other, theoretically it should not be possible to apply one specific formula to both parts of the curve.

Curve B of Figure 3 in my original paper is a representation of my modification of Sorby's relation. Considering only the deep well data, it seemed at first that this relation might be valid throughout the whole course of compaction. However, as is evident from the figure, it was not found possible to reconcile this curve with the actual data for low pressures, although my modification of Sorby's relation approaches this more closely than does Rubey's.

The final reason for believing that the equation which holds for pressure-porosity relations at high pressures does not apply at low pressures is consequent from trial calculations based on this idea. Rubey's computed figures for porosities at various depths in the Ranson well are derived from the equation

$$D=\frac{65{,}200}{D+1{,}970+652}.$$

The values thus calculated check remarkably well with the observed porosities. However, if the same calculation is made for a total depth of 2 feet, a porosity of 99 per cent is obtained. An overburden of 50 feet gives a porosity of 93 per cent; and at a depth of 100 feet porosity is still more than 86 per cent. As all of the figures are higher than the observed porosity of a 3-inch column of most muds, the failure of the formula at these pressures is evident.

15. However, notwithstanding these considerations, Rubey goes ahead to calculate by means of his formula the topographic relief on the post-Mississippian erosion surface, which he believes responsible for the 100 feet of structural relief of the Fairport-Natoma anticline in the Cretaceous beds of Russell County, Kansas. Using a calculated eroded thickness of 1,400 feet and constants of either 815 or 652, he arrives at a calculated topographic relief of 400 feet, which

he considers a reasonable result. Using his method I was unable to bring my results down to so low a figure, but this may be due to a difference in the method of application. However, it is obvious that his assumption of 100 per cent initial porosity would reduce the necessary relief considerably.

Rubey has objected to my estimate, based on all available data, of the average initial porosity for 100 feet of mud in the development of my pressure-porosity curve, on the ground that it weights too heavily the most important part of the curve in respect to calculations of structural effects. Yet he proceeds to make his own calculations by means of a formula which gives values for this important part of the curve which are clearly exaggerated and which consequently make worthless his estimate of the quantitative relation of structure to buried topography.

Even supposing Rubey's method of calculation were correct, he has overlooked the fact that the log of the Phillips well, "less than 15 miles east of the fold," shows less than 30 per cent shale in the basal 500 feet of Pennsylvanian sediments, and hence it is certainly possible that the column of sediments surrounding the hypothetical buried hill is less than 50 per cent shale.

However, overlooking all else in Rubey's Russell County calculations, I find that he has apparently failed to recognize the point of greatest significance in the whole matter: the long period of post-Permian erosion which cannot be assumed to have left a surface showing any particular expression of hypothetical folds due to settling over post-Mississippian topography. That Rubey's estimated 1,400 feet of eroded sediments, or any thickness of rock whatever, could have produced a closure of 100 feet at the present surface through 3,000 feet of already fairly well-compacted sediments about buried topography with a relief of 400, or even 600 feet, is nothing short of preposterous. Indeed, Rubey's speculation regarding the Russell County structure may now truly be set down as a "horrible example of the limits to which the theory has been pushed."

16. The writer made some observations of a general and theoretical nature on the characteristics of structures attributed to the compaction of sediments. These were included in the original paper under the heading "Character of Structures Produced by Vertical Compaction." It was expressly indicated that these observations were of a general nature and that no attempt was being made to apply them to specific cases; nor was any estimate being made of their quantitative importance. Rubey begins his discussion of this section as follows:

> Compaction may cause folds by some method other than that on which the calculation is based. For example, it would be useless to spread a bedroll on rough ground if the irregularities on the upper surface of the mattress were as great as those on the ground. The same thickness of bedding is deposited over the entire surface, but distortion of the mattress smooths out the irregularities more or less. The analogy is not perfect, but it illustrates another possible cause of increase of folding with depth over buried hills which I think Hedberg dismissed too readily. Clay landslides down the slope of a buried hill during or after sedimentation would also account for greater thicknesses of shale off structure. Sedimentation and compaction *pari passu* may be, as Hedberg assumes, the principal factor, but any stretching and squeezing of strata

comparable to the distortion of the bedroll mattress or any slipping of clay beds would vitiate the quantitative accuracy of calculation of the amount of closure on strata over a buried hill based on his assumption.

Mention was made in the original paper, as one of the possible causes, that thinning of strata over buried hills "may be due to a slight stretching of shale over the crest of the fold," but, as Rubey says, the subject may have been dismissed too readily, although not exactly belonging to the principal theme. Rubey's example of the bedroll is not clear. Certainly part of the advantage gained by spreading a bedroll over rough ground is due to the fact that the sharpness of irregularities is diminished by the same principle which makes dips decrease away from the concentrum in the case of concentric folding. Is not most of the other part due simply to difference in the degree of compaction of the mattress above ridges and above hollows? Also, is there any reason to suppose that "clay landslides down the slope of a buried hill during or after sedimentation" would account for greater thicknesses of shale off structure in beds overlying the buried hill?

17. The writer made the general statement that "increase of folding with depth does by no means necessarily imply an origin due to settling. It may be the result of simple concentric folding due to lateral forces or to gradual or intermittent uplift contemporaneous with deposition." Rubey says: "I cannot agree with him that parallel or concentric folding may be an adequate explanation of this characteristic." Certainly there was nothing in the original statement which could be construed into an estimate of the quantitative adequacy of the process, which can only be calculated in specific instances. Also, certainly there is no doubt but that it is theoretically possible for dips to increase with depth in the case of concentric folding.

18. The writer suggested four possible causes of the inclination of axial planes of structures, which would still be compatible with an origin due to settling. Rubey says: "His four possible explanations of inclined axial planes also seem to me unsatisfactory." The first is unsatisfactory because it accounts for only slight inclinations in the Mid-Continent field—a fact which in no way prevents it from being a "factor which may possibly have exerted influence in certain cases."

The second and fourth he considers as unimportant, as he thinks they are based on the "assumption" of parallel or concentric folds, which is "unwarranted where shale makes up large parts of the stratigraphic section." There is probably no such thing as a perfectly competent bed, and hence never perfectly parallel folding. On the other hand, perfectly similar folding must be rare indeed, and as long as there is the slightest trace of parallel folding there will be some tendency toward the shifting of the axis of structure of an asymmetrical fold toward the steeper flank. For example, consider the settling of muds over a vertical-faced fault scarp. Unless there is complete severing of strata in the plane of the vertical face, the resultant monocline in higher beds will be deflected toward the lower side of the fault plane. The third factor he considers "may possibly be an adequate one."

19. "Finally," says Rubey, "I cannot share Hedberg's optimistic belief that the porosity of shale beds may be a sensitive index of the metamorphism due to lateral pressure which a region has undergone." Certainly nowhere in my paper have I stated such a belief. My statement was: "Porosity thus becomes a fairly reliable index of the pressure which *rocks of this nature* [clays, muds, shales, etc.] *have endured*." The porosity of a sample of shale is in all cases only an index of pressure metamorphism which that particular specimen has undergone. Whether the degree of metamorphism of this specimen is representative of a whole region is another matter. Furthermore, I said "When porosity is high it is a very sensitive index of pressure"; but "the sensitiveness of the index decreases as porosities become lower." The truth of this statement should be apparent when it is considered that between 60 and 80 per cent, a pressure of less than a pound per square inch is sufficient to cause a decrease of 10 per cent in porosity. There was no statement that "shale beds may be a *sensitive* index of the metamorphism due to lateral pressure *which a region has undergone*," although in some cases this may be true.

20. Rubey continues: "It seems to me that the soft argillaceous rocks would not be called upon to transmit horizontal stresses, but that these weak strata would normally ride upon the deeper-lying, less compactible rocks during horizontal movements." That folds may commonly be due to pressure transmitted in the deeper, more competent rocks is such an obvious truth that it seemed superfluous to repeat it, and careful reading shows that none of my statements are incompatible with this idea. Probably the statement to which Rubey has given an erroneous meaning is the following: "The porosity of the fine-grained argillaceous sediments should be a valuable check on the plausibility of ascribing folding to the lateral transmission of stress *through these sediments* from some distant center of disturbance." However, it is to be noted that if porosities of shales may serve as an index of pressure metamorphism at all, they may be applied to any area in which carbon ratios of coals would be of value. All of Rubey's objections to the use of porosities of shales are equally applicable to carbon ratios.

In conclusion, the writer wishes to reiterate the opinion expressed in his previous paper, that adequate testing of the significance of the porosities of shale and their relation to pressure cannot be accomplished without the assembling of many more data than have hitherto been available. The ideas presented in these papers are intended to be chiefly suggestive, although based on all the data at hand. It is entirely possible that many of the opinions expressed and the tentative conclusions reached will have to be modified as a result of future investigations; but these may at least serve as a rough index of the quantitative importance of compaction until such time as further experimental and analytical work permit the formulation of more conclusive results.

HOLLIS D. HEDBERG

MARACAIBO, VENEZUELA
April 15, 1927

SOME QUESTIONS ON THE CAUSE OF THE SUBSIDENCE OF THE SURFACE IN THE GOOSE CREEK FIELD, TEXAS

L. C. Snider's article, "A Suggested Explanation for the Surface Subsidence in the Goose Creek Oil and Gas Field," in the July *Bulletin*, page 729, criticizing the explanation by Pratt and Johnson, is searching and thought-provoking. His alternative explanation is ingenious and merits consideration.

Dr. Snider accepts as a fact the observed subsidence, as does every one of a score of competent observers who have gone over the evidence with me on the ground. He questions only the proposed explanation for the subsidence.

The explanation offered by Pratt and Johnson is based on the conception that the sedimentary column at Goose Creek, consisting as it does of geologically young sediments, has not yet experienced nearly the full effect of the compacting forces to which buried sediments are normally subjected; that compacting at Goose Creek is accomplished principally through the elimination of the original water content of the sediments by pressure, due to the weight of overlying beds; and that any relief of the pressures which react at depth against the weight of the overlying column must accelerate the compacting process at the point of relief, and so permit incompetent overlying beds and the surface of the ground to subside.

Sedimentary beds undergo a progressive compacting of induration from the time they are deposited on the sea bottom until they are transformed into dense rocks. The relative consolidation or compacting of the beds beneath the surface at Goose Creek is indicated by comparing their water content with that of less compacted and more compacted material, respectively. It is well known that sea-bottom muds contain extremely large proportions of water. It is stated that samples taken 10 feet below the surface of the sea bottom consist of as much as 60 per cent water and 40 per cent solid matter. Core samples of clays encountered in drilling at Goose Creek consist of as much as 30 per cent water and 70 per cent solid matter. Core samples of Cretaceous shales from wells in the interior part of Texas contain 10 per cent water and 90 per cent solid matter. Thus it appears that Goose Creek clays have undergone but little more than one-half the induration they may be expected ultimately to experience.

The early wells drilled at Goose Creek encountered pressures up to 1,800 pounds per square inch in the deeper sands. These pressures have been relieved or entirely dissipated through the removal of oil, gas, water, and sand from hundreds of wells over the field. As oil, gas, and sand are removed, water comes into the sands to replace them; and as water is removed, more water comes in to replace it. This water does not come from a distance through the sands, because the sands do not persist over great distances. On the contrary, they are restricted laterally to small local lenses. It is reasonable to believe that some of this water comes into the depleted sands from the adjacent clays. Certainly before the pressures were relieved in the sands there must have been an established

equilibrium between the tendency to squeeze water out of the clay into the sands and the reacting pressures in the sands. When the pressures were relieved this equilibrium must have been disturbed and the tendency of the water in the adjacent clays to drain into the sand lenses in which pressures had been reduced must have been augmented. The total volume of gas (at original pressures), oil, water, and sand removed from the Goose Creek pool has been replaced by water from some source. This volume is estimated at more than five times the volume between the planes which represent the original surface and the present surface over the area of subsidence. If this volume of water, or any large part of it, did drain out of the clays with which the numerous sand lenses are interbedded, in the manner suggested by Pratt and Johnson, then a considerable volume reduction in the drained or dried clays would certainly result.

Dr. Snider interprets the percentages of water in clays, as expressed in the original paper, on a basis of the weight of the dried clays. These figures really express the water content of the original core samples, undried. He also speculates on the possibility of cracks forming in the dried clays underground as a result of shrinkage in drying. This contingency is remote. The clays are plastic enough to be deformed between the fingers and would flow laterally with great facility. Therefore, both lateral and vertical shrinkage would contribute to surface subsidence.

Dr. Snider considers it remarkable that most of the water removed from Goose Creek sands has come from the central portion of the oil field, and points out that commonly sands on the edges of oil fields contain more water than central wells. This is true, of course; but almost no water is removed from edge wells at Goose Creek, since edge wells are put on production only rarely. More wells are drilled in the central portion of the field and more producers are obtained there. The field as a whole yields water in direct proportion to the number of pumping wells operated, and from the area in which these wells are most numerous. The net result is that more water, as well as more oil and gas and sand, has come from the central portion of the field, where maximum subsidence occurred, than from the edges of the field.

Dr. Snider's suggested explanation for the subsidence at Goose Creek, namely, that oil, gas, and possibly water filled the sand reservoirs to the spilling point, as it were, so that the fluid and gases actually occupied otherwise vacant space above the top of the sand itself and against the overlying clay roof, cannot be summarily dismissed as impossible. Such a condition might prevail in lenticular sands, if they were adequately sealed and if sufficiently high pressures were generated. At Goose Creek, with no competent beds to sustain any part of the overburden on the sand reservoirs, pressures would apparently have to balance the weight of the entire geologic section above the reservoir before any free space could be maintained between the sand and its roof. No such pressures have been observed at Goose Creek. The gauged pressures are far from adequate. They are generally somewhat less than the full hydrostatic column on the sand, which is equal to approximately 50 per cent only of the weight of the

corresponding rock column; nor have we observed such high pressures elsewhere in this region.

The suggestion is obvious that before such pressures could be built up, the imprisoned gases would escape to the surface through pores and cracks, displacing the water seal in these openings. All our high-pressure fields in the Gulf Coast region do manifest copious gas seeps at the surface. Gas seeps are, in fact, our best surface criterion for establishing the relative promise for oil fields in any unexplored locality. This gas appears to be forced out and upward from the underlying sand reservoirs by the pressures with which we are acquainted in those reservoirs.

For these reasons the former presence of gas- or oil-filled spaces above the sand bodies in the reservoirs at Goose Creek appears to be doubtful.

WALLACE E. PRATT

HOUSTON, TEXAS
June, 1927

GEOLOGY OF GARVIN COUNTY, OKLAHOMA, AND THE ROBBERSON FIELD

I wish to call attention to two errors which appear in "The Geology of Garvin County, Oklahoma, and the Robberson Field," by Robert H. Dott and Robert Roth, *Oklahoma Geological Survey Bulletin 40-K*, May, 1927, Figure 3, page 28.

The well shown in Sec. 33, T. 5 N., R. 9 E., with an elevation on top of the Hunton limestone of 3,685 feet below sea-level, should be located in Sec. 33, T. 5 N., R. 8 E.

With the well properly located, the dip is much steeper than shown. Instead of the flattening across Range 7, as shown by this map, the dip is uniform from the crest of the Hunton Arch to this well, and the fold is essentially symmetrical.

The other error is the total depth shown for the well in Sec. 10, T. 6 N., R. 2 E., which stopped in marine Pennsylvanian strata at 4,900 feet, instead of 4,015, as shown.

These corrections will appear in the final three-volume edition of *Bulletin 40*, together with additional data obtained from wells drilled since this map was prepared.

ROBERT H. DOTT

TULSA, OKLAHOMA
June 21, 1927

EFFECT OF GRAVITATIONAL COMPACTION ON THE STRUCTURE OF SEDIMENTARY ROCKS

I have studied the paper of Mr. H. D. Hedberg, published in the November, 1926, *Bulletin*, together with the discussion published in the June, 1927, *Bulletin* by Mr. W. W. Rubey.

Mr. Rubey maintains that the results presented by Hedberg seem more

sweeping as to quantitative application than their mathematical accuracy warrants, the mathematical accuracy being criticized because of the assumption of an initial porosity of 50 per cent in compiling the gradient curve. An assumption must approximate an average condition in order to be tenable, and I think Mr. Hedberg presents enough information in his paper to indicate that the initial porosity of 50 per cent is reasonable. Relative to the quantitative application of the tables presented by Mr. Hedberg, I think Mr. Rubey has overlooked that the tables are to be applied necessarily under the assumption that the geological section in the case to be tested is entirely shale, whereas the logs of the Kansas wells reveal an aggregate thickness of shale ranging from 30 to 60

TABLE I

Structure, Name, and Location	Surface Dip per Mile	Estimated Overburden	Height of Surface above Pre-Penn. Contact	Closure, per Hedberg for 100-ft. Hill	Hill Necessary to Account for Surface Dip	Known Pre-Penn. Relief
Beaumont anticline T. 26 S., R. 9 E..	90 E.	7,000	2,500	15	600	None
Elmdale dome T. 20 S., R. 7 E..	250 E. 400 S.	6,500	1,900	16	1,600 2,500	300
Burns dome T. 23 S., R. 5 E..	240 E. 400 S.	7,000	2,300	16	1,500 2,500	425
Eldorado dome T. 25–26 S., R. 4–5 E.	160 E. 200 S.	7,000	2,350	15.5	1,000 1,300	500
Augusta dome T. 28 S., R. 4 E..	80 E. 130 S.	7,000	2,500	15	560 860	350 (Fault, 50–250)
Oxford dome T. 31 S., R. 2 E..	250 E. 350 S.	7,500	2,900	12	2,000 3,000	350
Fairport anticline T. 11 S., R. 15 W.	100 W.	5,000	3,000	8.3	1,200	250

per cent only. Having these limitations in mind, I have applied the quantitative data to some of the major folds in Kansas, with results as shown in Table I (figures given in feet).

The writer realizes that the estimated overburden here shown affects the calculations as to hill necessary to account for observed structural relief, and, in estimating same, has attempted to use a figure in accord with Hedberg's porosity observations, with known geological sections and with reasonable estimates of eroded sediments. Should it be possible that the estimates are exaggerated, inspection of the table presented by Hedberg will show that the hill necessary would be greater if a lesser estimated overburden were used.

The results here shown in tabulated form indicate that the hill necessary to account for the surface structural relief is so much greater than the known heights of the pre-Pennsylvanian relief, under the assumption that the entire section over the hill is shale, that compaction of sediments with overburden or

differential settling as termed by Blackwelder[1] certainly is not a satisfactory explanation of these folds, though it may explain some of the minor surface folds of Kansas.

Geological observations have not been entirely in accord with Blackwelder's theory in regard to Kansas, though that has been accepted by many in Kansas and other places. For example, the Beaumont anticline, which has a reverse in one place of 90 feet, shows in cross-section all the characteristics of a truly compressional fold, including a full section of "Mississippi lime" folded symmetrically with other overlying strata.

Mr. Hedberg has set forth a field for interesting research of economic significance in interpreting the continuity of observed minor surface or shallow core-hole structures with depth, and it is to be hoped that members of the Association will endeavor to collect shale samples from deep wells in order that additional information may be available to those interested.

CHARLES E. STRAUB

DIXIE OIL COMPANY, INC.
WICHITA, KANSAS
June 27, 1927

[1] Eliot Blackwelder, "Origin of Central Kansas Oil Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), pp. 89–94.

REVIEWS AND NEW PUBLICATIONS

The Structure and Stratigraphy of Florida, with Special Reference to the Petroleum Possibilities. By Stuart Mossom, 17th Annual Report, Florida Geological Survey, Tallahassee, 1926. Pp. 169–275.

In this bulletin published by the Florida Geological Survey, the author precedes his discussion of the stratigraphy of Florida with a table of the surficial formations. Several Pleistocene formation names which at different times have appeared in the geologic literature of Florida have been wisely omitted and included under the term "Pleistocene Marls," undifferentiated. "All of the rocks of the Everglades area lying above the Caloosahatchie marl, with the exception of the Miami Oölite, are lithologically and paleontologically similar, and little accuracy can be secured in mapping them on the basis of existing data."

Under the heading "Underlying Formations" it is pointed out that in peninsular Florida the formations beneath the Ocala limestone, Jackson Eocene, are unknown, and a study of well samples reveals nothing indicative of an age older than upper Eocene.

A review and summary are made of the literature of several years ago, in which it was announced that Foraminifera indicative of the Fredericksburg series of the Lower Cretaceous of Texas were found in peninsular Florida, with the conclusion that the Ocala limestone, Jackson Eocene, in this region was only about 40 feet thick and underlain by nummulitic beds of the Lower Cretaceous.

Later this diagnosis was found to be in error, and the beds in question were referred to the upper Eocene.

The author discusses the formations found at the surface in Florida.

The Ocala limestone is described first, and a list of its more common megascopic fossils given which would enable the field geologist readily to identify it. The characteristic Foraminifera are also listed. The thickness of the Ocala limestone in Florida is not known, as the base of the formation is not exposed. The greatest exposed thickness is 115 feet. Well samples indicate that Ocala fossils continue downward into a hard brown limestone. Sink-hole topography is characteristic of the area of Ocala outcrop in peninsular Florida.

The Oligocene is represented by the Marianna limestone and the Glendon formation, which together comprise the Vicksburg group.

The Marianna, a soft chalk-like limestone, outcrops in a small area in Jackson County, central-western Florida. Its present thickness is 33 feet, although some of its upper part may have been removed by erosion.

The Glendon formation occurs in western Florida, where it is recognized in two facies: where weathered, by "variegated reddish-yellow residual sands and

clays"; where unweathered, by soft pure cream to light yellow compact limestone.

The Miocene is represented by the Tampa formation, Chattahoochie formation, Alum Bluff group, Jacksonville formation, and Choctawhatchie marl.

The Tampa formation is chiefly a light gray to yellow limestone occurring on the west side of peninsular Florida.

The Chattahoochie formation consists of argillaceous limestone and sandy clay, and occupies only a small area in the central-west part of the state.

The Alum Bluff group, the most widely distributed formation in the state, is made up of the Chipola, Oak Grove, and Shoal River members. The Chipola formation is widely distributed in the northern and central parts of the state. In addition to limestones, marls, sands, and sandstones, it includes the well-known fuller's earth beds in western Florida and the phosphatic sands.

The Oak Grove sand occurs only in a small area in the northwestern part of the state.

The Shoal River formation is likewise found only in a limited area in western Florida.

The Jacksonville formation is found only in northeastern Florida, and is of limited extent.

The Choctawhatchie marl is a marine formation restricted to western Florida.

The Pliocene of Florida consists of several marine and estuarine deposits found in various parts of the state and separated into a number of formations, some of which are contemporaneous.

The Pleistocene likewise is represented by a number of formations in practically all parts of the state. These also are largely contemporaneous.

The author divides the state into geographic subdivisions, as the Pensacola area, Marianna-Chipley area, Quincy area, Tallahassee area, Ocala area, Brooksville area, Jacksonville area, Daytona area, Kissimmee area, Tampa area, Fort Myers area, Miami area, and the Key West area. In each of these divisions he discusses in detail the stratigraphic and structural data available, gives logs of the wells which have been drilled, and a list of the fossils which have been obtained from well cuttings.

It is pointed out that an area in northwestern Florida lying just west of Apalachicola River is structurally high, with the formations dipping southeast, south, and southwest. It is not known, however, whether any local structures exist on which there is sufficient closure to warrant drilling for oil. A well in this area drilled to a depth of 4,912 feet encountered Miocene, Oligocene, Eocene, and Upper Cretaceous. The Upper Cretaceous was penetrated to a depth of approximately 2,200 feet.

Wells drilled in the peninsula of Florida show the section to be predominantly a limestone section. No fossils older than upper Eocene have been found.

The author points out that carbonaceous material is found in the formations in western Florida, in addition to limestones, sands, and greensands; whereas

limestones predominate in the unexposed section of the peninsula. The peat, lignite, and coal are found only at shallow depths. The author makes the point that carbonaceous deposits are necessary for the formation of petroleum, and in producing areas carbonaceous shales of considerable thickness are immediately associated with the producing beds. This, therefore, makes peninsular Florida look unpromising for petroleum.

This report is accompanied by a structural map of the state with contours on the top of the Ocala limestone. This map indicates two structurally high areas in Florida, one of which is the central part of the peninsula and the other the Marianna-Chipley area, west of Apalachicola River. The peninsular structure shows nothing but a limestone section. The Marianna area is evidently not closed on the north. It, however, has carbonaceous material in the section, and would no doubt be the most promising area for petroleum explorations.

On the whole the report is well prepared and the author has taken great pains to get all the data in the state available and in shape for this presentation in such a way that it will be of considerable help to anyone contemplating work in Florida with a view to an investigation of the petroleum possibilities there.

OLIN G. BELL

LAREDO, TEXAS
June 23, 1927

RECENT PUBLICATIONS

GENERAL

"The Interpretation of Crude Oil Analyses," by N. A. C. Smith. *Report of Investigations Serial No. 2806, U.S. Bureau of Mines*, Washington, D.C. Free.

Oil and Petroleum Manual, by Walter E. Skinner, 15 Dowgate Hill, London, E.C. 4. 1927. Oil Trade, 350 Madison Avenue, New York, N.Y. Detailed particulars of oil companies operating in all parts of the world. 430 pp. Demi 8vo., bound in red cloth. Price, $2.50 (post free).

ILLINOIS

"Map of Illinois Mineral Industries and Directory of Illinois Mineral Operators." *State Geological Survey*, Urbana. New wall map (31×49 inches). Shows locations of oil fields. Price, $0.50.

"Illinois Petroleum." *Press Bulletin Series No. 9, State Geological Survey*, Urbana. Structure map of Galesburg quadrangle in Warren and Knox counties and discussion of oil possibilities. Price, $0.25.

TEXAS

"Analyses of Spindletop, Texas, Crude Oils," by A. J. Kraemer and Peter Grandone. *Report of Investigations Serial No. 2808, U.S. Bureau of Mines*, Washington, D.C. Free.

VENEZUELA

"Properties of Typical Crude Oils from the Producing Fields of Venezuela," by A. J. Kraemer. *Report of Investigations Serial No. 2807, U.S. Bureau of Mines*, Washington, D.C. Free.

THE ASSOCIATION LIBRARY

Headquarters acknowledges library accessions:

ARKANSAS

From Carey Croneis:

"Sharks from Fayetteville Formation."

"Notes on Cycloceras and Associated Genera."

LOUISIANA

From R. A. Steinmayer:

Proceedings of the Louisiana Engineering Society, Vol. 13, No. 2, April, 1927, containing "A Geological Survey of the Sub-Aqueous Strata of Lake Pontchartrain, New Orleans, Louisiana."

TEXAS

From T. W. Stanton:

"The Cretaceous of Texas."

From Bureau of Economic Geology of the University of Texas:

"A List of the Common Minerals and Mineral Products of Texas, with Notes on Occurrence and Use."

AUSTRALIA

From Arthur Wade:

"The Possibility of Oil Discovery in Queensland."

"Petroleum: Report on Investigations Made in New South Wales."

"Report on Petroleum Prospects in Parts of Western Victoria, South Australia, and Western Australia."

"Petroleum Prospects: Kimberley District of Western Australia and Northern Territory."

"Report on Petroleum in Papua."

THE ASSOCIATION ROUND TABLE

THE MAILING LIST

Members who do not receive the *Bulletin* promptly about the twentieth of each month (allowing necessary time for mail delivery) should notify headquarters immediately and give their present address. Lost or strayed *Bulletins* will be replaced *gratis* only when headquarters is notified within three months of date of issue. Members leaving forwarding addresses at their homes or offices should give definite instructions to attach the necessary stamps for forwarding, else the post-office will return the *Bulletin* to Association headquarters at Tulsa. It is not sufficient to write the forwarding address on the wrapper; forwarding postage must also be attached. A forwarding address left at the post-office will not be honored for second-class matter unless postage is provided.

Headquarters is endeavoring to give Association members prompt service. More than one hundred changes in the mailing list are made monthly. The *Bulletin* is issued from the press promptly. But prompt delivery cannot be assured unless members keep headquarters informed of correct addresses.

TEN-VOLUME INDEX

The new topical index to the full ten volumes of the *Bulletin* is ready for distribution this month. This is a comprehensive classification of subject matter and authors compiled by our editorial secretary, Miss Daisy W. Heath. It includes, in rearranged form, the first six-volume index prepared in 1923 by J. R. Pemberton. An outstanding feature is the facility for finding the titles of papers that have appeared in the *Bulletin*. All references to major articles are indicated in italics, thus distinguishing these most important subjects from subordinate topics scattered through the text. For added convenience, different grades of subordinate items are indicated by two indentations under the principal reference.

The *Bulletin* is becoming increasingly valuable as an authoritative reference. This complete index makes its information readily available. To those geologists who are so fortunate as to possess a full set of the *Bulletin*, the new index is a necessity for the efficiency of their library. To those who have only the back numbers yet available, the index is still more valuable.

The size and binding of the index are uniform with the *Bulletin* itself. The price is $2.00. Checks should be made to the American Association of Petroleum Geologists and sent to Box 1852, Tulsa, Oklahoma.

AT HOME AND ABROAD

At a recent election of the Panhandle Geologic Society of Amarillo, Texas, the following officers were elected: president, C. DON HUGHES, Empire Gas & Fuel Company; vice-president, G. S. LAMBERT, Phillips Petroleum Company; secretary-treasurer, C. SCHNURR, Mid-Continent Petroleum Corporation. Meetings are held on the first and third Friday evenings each month in the Round-Up Room, Amarillo Hotel. The retiring president of this organization is C. MAX BAUER.

ARTHUR WADE, consulting geologist, 16 Basinghall St., London, E.C. 2, is the author of an article, "Two Shallow Oil Fields in Texas," in the April number of the *Journal of The Institution of Petroleum Technologists*. The same number contains a discussion on "The Significance of Surface Oil Indications" by DONALD C. BARTON, Petroleum Building, Houston.

ALEXANDER DEUSSEN, vice-president of the Marland Oil Company of Texas at Houston, is recovering from a prolonged illness.

PAUL WEAVER, of the Gulf Production Company at Houston, makes use of the airplane in his geological work.

LOUIS A. SCHOLL, recently of Pittsburgh, is now with The Texas Company, Drawer F, Houston.

W. A. CLARK, JR., is situated at Coalgate, Oklahoma, as geologist for the Indian Territory Illuminating Oil Company.

WALT M. SMALL is now situated at 412 Preusser St., San Angelo, Texas.

H. I. TSCHOPP has moved from Puerto Mexico to Switzerland. His address is Hauptpostlagernd, Basel.

F. JULIUS FOHS, vice-president of the Humphreys Corporation, recently spent his vacation in Europe.

JACK DOYLE, of the Humble Oil & Refining Company at Shreveport, Louisiana, spent a week in St. Louis in June.

D. L. CALDWELL, who was in the geological department of the Associated Oil Company in California, recently resigned and is now with the Barnsdall Oil Company at Los Angeles.

THE KANSAS GEOLOGICAL SOCIETY, Wichita, Kansas, has elected new officers as follows: president, L. W. KESLER, district geologist for the Sinclair

Oil and Gas Company; vice-president, JOHN R. REEVES, of the Empire Gas and Fuel Company; secretary-treasurer, JOHN L. GARLOUGH, consulting geologist, 612 Brown Building. ANTHONY FOLGER, of the Gypsy Oil Company, and F. G. HOLL, consulting geologist, are members of the board of directors with the officers.

ARTHUR IDDINGS, formerly of Toronto, Canada, is assistant manager of the International Petroleum Company at Negritos, Peru.

F. M. RICKS, of Tonkawa, Oklahoma, who received a Bachelor of Science degree from the University of Oklahoma in 1927, has secured a position as instrument man with the Skelly Oil Company in El Dorado, Kansas.

JAMES FITZGERALD, JR., has accepted a position as field geologist with the Skelly Oil Company at El Dorado, Kansas.

H. P. BYBEE, of the Dixie Oil Company at San Angelo, Texas, spent his vacation in Indiana in June.

W. A. WALDSCHMIDT is now with the Mid-West Refining Company at Denver, Colorado.

H. R. ERDMANN has moved from Tampico, Mexico, to 59 Kahlenberger Strasse, Vienna XIX², Austria.

J. W. BEEDE, of the Dixie Oil Company, has been working in Indiana.

MR. and MRS. D. DALE CONDIT left India early in May and spent a vacation in southern England. Mr. Condit's address is Carr Brothers, 65 Broadway, New York City.

DJEVAD EYOUB, of Laredo, Texas, visited New York this summer. His present address is Apartado 285, Tampico, Tamps, Mexico.

FRED B. ELY has been in Venezuela a few months making geologic studies in the northern coastal country.

N. H. DARTON recently returned to Washington from Venezuela, where he spent six months exploring the geology of part of the eastern slopes of the Andes.

IAN CAMPBELL, of Louisiana State University, gave an interesting account to the Houston Geological Society, on June 4, of his work for the Vacuum Oil Company on correlation by means of heavy minerals in the Lockport field in southwestern Louisiana.

The Houston Geological Society had another interesting meeting on June 16, when R. C. MOORE showed them and their guests his reels of his exciting trip through the Grand Canyon of the Colorado.

DONALD C. BARTON, consulting geologist and geophysicist, 717 Petroleum Building, Houston, Texas, will act as general adviser on geophysics and as specialist on the Eötvos torsion balance, magnetometric surveys, salt domes, and the Gulf Coast.

ARLINGTON WAGGONER, of the Amerada, is reported to have taken unto himself a wife.

R. C. MOORE has been making a circular tour through the Gulf Coast and the Mid-Continent, collecting information.

ANDREW GILMOUR, of the Geophysical Research Corporation, has been transferred from Houston to Tulsa and put in charge of the Amerada torsion balance and magnetometer work.

PAUL MORSE, until recently of the Moody Corporation, is now with The Texas Company.

E. O. ULRICH, of the U. S. Geological Survey, was in Europe last month on his annual vacation.

GRANT BLANCHARD is in charge of development in southeastern New Mexico for the Marland Oil Company. His office is in the City Hall Building, Carlsbad.

RALPH ARNOLD and associates, incorporated as the Standard Petroleum Company of New Mexico, will drill several wells in the Rocky Mountain district.

W. B. HEROY, of the Sinclair Exploration Company, 45 Nassau St., New York, went to South America in June.

JOHN R. SUMAN, of the Humble Oil & Refining Company, Houston, took his vacation in the west and attended the standardization conference of the A. P. I. at Colorado Springs, in June.

DAVID DONOGHUE, of the Texas Pacific Coal & Oil Company, Fort Worth, is back after a brief vacation last month.

E. DEGOLYER and WALLACE PRATT are members of the technical relationship committee of the A. P. I., which met at French Lick, Indiana, June 20.

E. BINNEY, of Yale University, and VICTOR COTNER have been investigating the natural gas possibilities of the Baxter Basin district relative to supplying Salt Lake City with gas.

R. A. STEINMAYER, of Tulane University, New Orleans, is the author of a paper on "A Geological Survey of the Sub-Aqueous Strata of Lake Pontchartrain, New Orleans, Louisiana," in the April number of the *Proceedings of the Louisiana Engineering Society.*

CLYDE M. BENNETT, vice-president of the Louisiana Oil Refining Corporation, Shreveport, has been elected president of the Trinidad Oil Fields, Inc., an allied interest, and has moved to New York City.

TSUNENAKA IKI, professor of petroleum engineering in Tokyo Imperial University, and KUNIO UWATOKO, assistant professor of geology in Hokkaido Imperial University at Sapporo, Japan, have been visiting American and British oil fields and refineries.

WILLIAM L. RUSSELL is in the geological department of the Venezuelan Gulf Oil Company at Maracaibo.

J. F. HOSTERMAN, geologist for the Amerada Petroleum Corporation in the Shreveport district, has been transferred to company headquarters at Tulsa.

J. M. MACDONNELL has returned to the United States after a trip around the world.

It is reported that a new oil well good for 2,000 barrels a day has been completed at Byoritsu, north of Taiwan, Formosa. There was no commercial production in the island heretofore, but small quantities of oil in pits were discovered many years ago by the Chinese.

PHIL K. COCHRAN, of the Standard Oil Company of New Jersey, has returned from Venezuela to the United States.

ARNOLD S. BUNTE is with the Roxana Petroleum Corporation at Crowell, Texas.

BRUCE HARRY HARLTON and MISS LUCILLE CAROLYN HARDY were married at Tulsa, Oklahoma, June 28.

The Fourth International Petroleum Exposition will be held at Tulsa, Oklahoma, September 24 to October 1, inclusive. This great exhibit of oil-field equipment and methods will be held on the new exposition grounds during the week of the Tulsa State Fair.

VIRGIL B. COLE, of the Venezuela Gulf Oil Company, stationed at Maracaibo, returned to the States last month.

THEODORE CHAPIN has moved from Laredo to Tampico, Mexico, with Cia. de Terrenos Petroliferos "Imperio," S. A.

HUGO R. KAMB, of the Mid-Kansas Oil & Gas Company, Tulsa, was married on June 18 to Miss Hazel Johnson, of Minneapolis, Minnesota.

FRANK A. HERALD, of Herald Brothers, consulting geologists, 303 Cosden Building, Tulsa, has returned from a business trip into west Texas and New Mexico.

WALTER A. VER WIEBE is now at Wichita College, Wichita, Kansas.

C. S. DIETZ has been appointed deputy state geologist of Wyoming.

W. T. THOM, JR., and EDMUND M. SPIEKER are to make another government study of the geology of the Teapot Dome Naval Reserve.

K. B. NOWELS, in charge of the U. S. Bureau of Mines experiment station at Laramie, Wyoming, has been studying conditions in the Salt Creek field.

The petroleum division of the A. I. M. E. will meet at Fort Worth, Texas, on October 19 and 20, with headquarters at the Texas Hotel. Four technical sessions will include papers on air-gas lift, air-gas lift and gas-oil ratios, use of

electricity in oil-field operations, and handling congealing oils and paraffin. The program is being arranged by J. B. UMPLEBY, vice-chairman, 710 Chautauqua Avenue, Norman, Oklahoma.

F. G. CLAPP left for Persia last month on an extensive business trip. His address is c/o American Legation, Teheran, Persia. Mr. Clapp is maintaining his permanent address, however, at 50 Church St., New York.

The American Petroleum Institute technical committee which met at French Lick Springs, Indiana, in June, submitted a report recommending that technical activities of the oil industry be co-ordinated and concentrated in the institute without necessarily affecting the activities of other technical societies.

W. G. SKELLY, president of the International Petroleum Exposition to be held at Tulsa September 24–October 1, has appointed the following committee on scientific and technical affairs: ALF G. HEGGEM, chairman; CHARLES N. GOULD, vice-chairman; FRANK C. GREENE, LUTHER H. WHITE, SIDNEY POWERS, ROBERT H. WOOD, FRANK A. HERALD, W. L. FOSTER, W. VAN HOLST PELLEKAAN, GEORGE MATSON, J. M. MCFARLAND, JOHN M. LOVEJOY, JAMES H. GARDNER, C. K. FRANCIS, W. B. WILSON. The geological exhibits committee is composed of FRANK C. GREENE, chairman; LUTHER H. WHITE, ROBERT ROTH, ROBERT H. WOOD, and FRANK A. HERALD.

This Association is to have a booth at the International Petroleum Exposition at Tulsa, September 24—October 1. This is to be maintained for the purpose of general information on the Association's work and activities. Publications will be on sale.